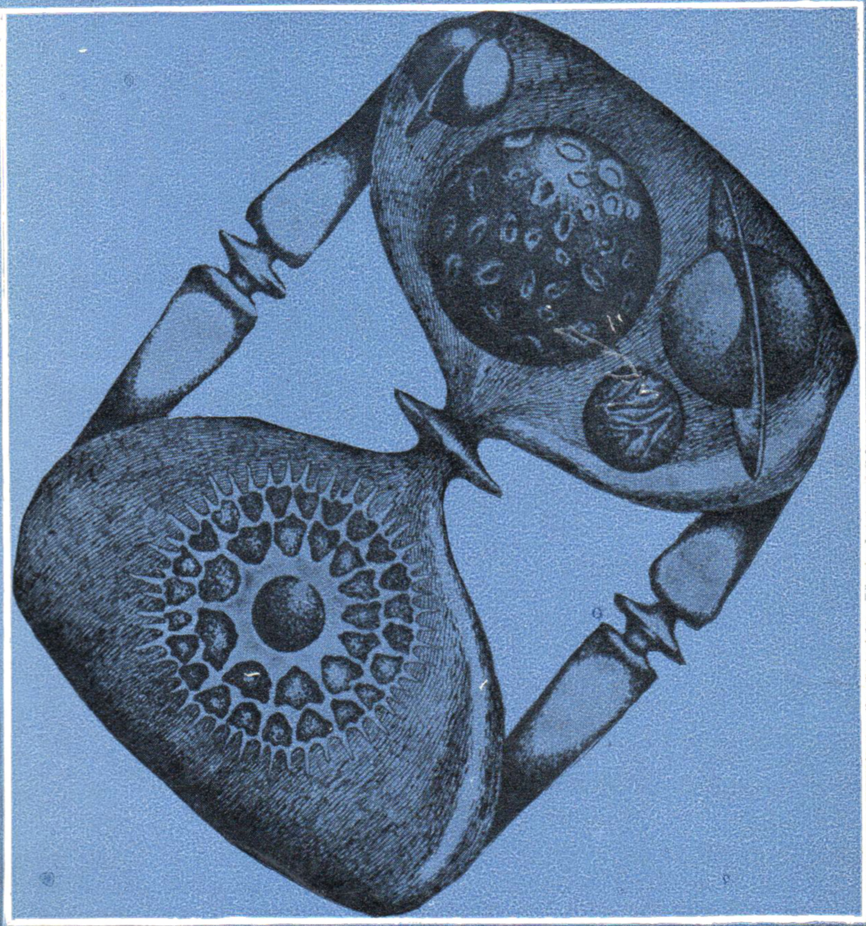
E.I. PARNOV

At the Crossroads of Infinities



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About the book

At the Crossroads of Infinities is a story about the struggle of ideas out of which the modern physical picture of the world was born. Can anything move faster than light? Is the universe finite or infinite? Is time reversible? What lies at the basis of the realities which we perceive as space, time or matter? These are the questions taken up in this book. And more, for it also tells of the roads of knowledge, of the way man has probed the mysteries of the infinitely large and infinitely small, yet at root integral world.

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НА ПЕРЕКРЕСТКЕ БЕСКОНЕЧНОСТЕЙ

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МОСКВА

E. I. PARNOV

At the crossroads of infinities

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CONTENTS

Face to Face with the Universe

In his letter "To a Reader", Karel Čapek described the contents of his novel *The Meteor* as follows:

"This is a story about the ways of cognition—incidentally, and begging your pardon, but why do people find cognition so terribly dull? Thus, in this story I have attempted to show how one and the same real fact can be interpreted according to the different ways our cognition of the world may proceed, for even the smallest fragment of reality is something tremendous: it lies at an intersection of different roads and is discoverable from diametrically opposite aspects.... We men have a slice of the universe for us to investigate, we penetrate its depths in many ways, we probe it with our actions, our science, poetry, love, religion, and they require different methods of measuring the world."

Only the size of this extract prevented me from making it an epigraph to this book.

As I sat before the first clean sheet of paper visions of man and the earth passed before my eyes. Man peering out of a dark cave and staring up at the sky until the distant stars kindled a light of response in his eyes. A vague uneasiness in his breast, a song at the fire—what else did he have with which to measure the void laying before him? Centuries and millennia rolled by. The concepts of the earth and heaven expanded to the dimensions of the universe. Human thought has had to grope its way through murky mazes, it has hibernated for centuries and floundered in the pitfalls of delusions and contradictions, yet

man has inevitably emerged triumphant from his struggle with eternal, inexhaustible Nature.

And now, too, his mind seeks to probe the depths of the universe and the fundamentals of matter. He stands at a crossroads of infinities. One road leads him into a world of galaxies, where fleeing matter attains sub-light speed, the other, into a microworld of vanishingly small spatial and temporal dimensions and strange, dual manifestations of the laws of probability.

Let us cast our eyes over the hazy voids which man so stubbornly tries to fathom. The known portion of the universe extends for approximately 10^{10} light-years, or 10^{28} cm. Man is smaller than the universe by a factor of 10^{26}. The dimensions of our planet make it impossible for us to comprehend even approximately the vastness and frightening meaning of this difference. But man is great if only because he has succeeded in spanning it. Take the other road to infinity, which leads into the world of elementary particles. The smallest of the known distances is 10^{-14} cm. It differs from the greatest by a factor of 10^{42}. These are the limits of modern knowledge, the measured sections of the roads. The number 10^{42} is so great that it is impossible to offer a meaningful picture of its true magnitude. An example from Kenneth Ford's book, *The World of Elementary Particles*, in which he attempts to assess the number 10^{42} in terms of conventional images, is as good as any other.

Suppose the number of people increased to 10^{42}. The globe is capable of holding some 10^{15} persons standing side by side. There are around 10^{23} stars in the universe. Assuming that each star has 10 planets, there are 10^{24} planets. Well, by standing people side by side on all of them we could make place for 10^{39} persons, still much fewer than 10^{42}

Now consider time. Man's average life expectancy is 70 years. Civilization is several thousand years old. It will be for other civilizations to judge what we have achieved, or failed to achieve in the time at our disposal.

The smallest known distance is 10^{-14} cm. Light travels it in 10^{-24} sec. This, then, is the smallest time interval, and it lies far beyond the limits of all known methods of time measurement. The greatest time interval we know is the "lifetime of the universe". By this is meant the time the universe has been expanding, estimated at anywhere between 10,000 million and 30,000 million years, or about 10^{18} sec. A comparison of these intervals yields the staggering number 10^{42} sec. These are the temporal dimensions with which man, who lives 10^{8} sec, has to deal. Incidentally, the coincidence of the time and distance intervals is not fortuitous. The remotest sections of the universe are receding from us at velocities approaching that of light. These, too, are the velocities of particles of the microworld. The speed of light unites the two infinities, the infinity of vastness and the infinity of minuteness. And we are at the crossroads. The habitual everyday world about us knows no such speeds. Only the human intellect can cope with domains where light is a measure of speed.

These are the dimensions of space and time. There remains matter. It changes with time and moves through space, it constitutes our essence: Nature realizes itself in *Homo Sapiens*. Matter has many faces and its manifestations are infinite. But there is one thing characteristic of all matter, mass. Let us try to assess the approximate mass of the universe. It contains 10^{23} stars. An average star weighs 10^{35} g. Hence, the mass of the universe is something like 10^{58} grams. Each gram contains about 10^{24} protons. A rough estimate thus yields that the known portion of the universe contains 10^{82} protons. A man weighs about 10^{5} g. He contains approximately 10^{29} protons. His brain, however, is capable of comprehending the number 10^{82} and "weighing" the universe.

This is the image of man that formed in my mind as I worked on this book. Almighty Man who has traced the confines of the universe has replaced the star-counting cave-

man. And I felt that I understood why the mysteries of space, time and matter excite and attract our imagination so much. Not for the sake of the cold light of abstract truth does man so stubbornly assault the secrets of the universe. It is not only for the sake of technological progress and material affluence that he seeks to fathom the depths of the macro- and microworld. Man's main, and not always realized, incentive for quest lies within him.

When we speak of the limits of the universe we imply the limits of knowledge. Temporary limits, to be sure, but nevertheless limits. In probing the universe man probes his own brain. The nature of his boldest and "maddest" theories is determined by his way of thinking. That is why the secrets of the cosmos and the microworld excite and attract us. They are a mirror which reflects our capability for knowledge. And man is born for knowledge. This is the meaning and the purpose of civilization. Which is why man will never stop looking into the mirror of the universe.

PART ONE

Looking Back

THE SOURCES

What do we know of the philosophical views of the ancients? Tens of thousands of unique manuscripts perished in the fire that gutted the Alexandrine libraries. A similar fate befell 200,000 volumes in the library of Pergamon, the library of the Temple of Jerusalem, many thousands of other books. Lost is the famous collection of Pisistratus in Athens, destroyed are the parchments in the secret repository of the Temple of Ptah in Memphis.

Random fragments, occasional shreds, enigmatic echoes of forgotten knowledge are all that reached us from vanished civilizations. During the conquest of Mexico Bishop Landa had burnt almost all the codices of the Mayas and today every new archaeological find topples the speculations of previous scholars. Our distant past is a long blank stretch broken here and there by landmarks of trustworthy facts. It is a fact that electric dry batteries were made hundreds of years before Christ and coins struck in 235 B.C. contain nickel. The serially joined batteries from the cesspools of ancient Bagdad can be seen in a museum. Incidentally, for a long time they were regarded as curious ritual objects. It was pure chance that an engineer who happened to visit the museum realized the real purpose of the little stacks of metal and resin. And how many mysteries are still awaiting their explanation! To this day men argue heatedly about the mammoth stone spheres scattered over a large area of Central America which present a chart of the constellations as they once were, the column of pure iron in India and the ancient Indian monuments which are alleged to contain information about the diameter of the hydrogen atom. It is not our purpose to question what is true and what is not. The point is that we still know very little about ancient civilizations.

In ancient monuments it is often hard to distinguish scientific notions from black magic, philosophy from poetry, cosmology from mythology. The ancient Babylonian epos, the ancient Hebrew book of Zohar, the Indian Ramayana and Mahabharata did not merely present a garbled and obscure reflection of the world: they reflected it syncretistically, they present us with a methodology of knowledge in which the scientific is inseparable from the artistic. In old books one can find pictures of the earth resting on three whales swimming in an ocean, or on three elephants standing on a turtle. But this doesn't mean that that is just how the ancients pictured the world to themselves. It is hard for us to judge of their true views, which are often presented symbolically. It would be wrong to directly identify mythology with philosophy, but nor can one completely separate mythology from man's first naive notions of surrounding reality. There can be no doubt that the lives of Rama and Krishna, Madruk and Oziris, Saturn and Chronosus contain symbolic interpretations of space, time and the basic elements thought to constitute the essence of all real things. The ancients did not know physics in our sense of the word, but they created the embryo of a discriptive science which one could call "fantastic physics".

However, it is time to wind up our rather long-winded introduction and proceed from myths to the ancients' ideas concerning the primary essence of the universe. These notions are of great value to us, for it is only now that science is preparing to answer the question asked since time immemorial: what are all things made of?

Men's advance toward knowledge has been slow and tortuous, along a thorny road of bitter disappointments, errors, sudden ascents and falls. It has been a stubborn pursuit toward one goal, a pursuit without rest. At the beginning of this road men frequently sought to penetrate the unknown with the help of prayers and invocations. Only later did the spontaneously accumulated knowledge produce the shoots of the mighty tree which we call contemporary science. They gleaned their practical experience from life, experience also served as their nutrient medium.

The idea of a primary matter underlying the universe appeared in the ancient East. According to the tenets of the ancient Indian Vaiseshika school, everything consists of minute material particles. In China, as in Egypt, various

notions that sprang from black magic and superstitions developed into a rigid system of religious conceptions of the surrounding world. All truths had to meet the system's requirements. Thus, according to ancient Chinese teachings, all things originated as the result of the interaction of the two principles, *yang* and *yin*, and the very reality of the world rests on the unity of their contradictions. *Yang* denoted the male and *yin* the female principle. *Yang* was associated with the sky, the sun, all active, positive qualities; *yin*—with earth, darkness, all passive, negative qualities.

Somewhat apart stand the civilizations that evolved on the American continent. The Maya's knowledge in astronomy was remarkable and surpassed all the ancient astronomers of the East ever got to know. In its conceptions of time the Mayan civilization has no rival. The Mayas attached such tremendous importance to the very course of time that it developed into an obsession, the focal point of their daily life. This mysterious people actually became the slave of their calendar. Mayan history, philosophy or religion cannot be understood outside the context of the calendar. Even their architecture was closely linked with astronomy. The Mayas believed that the movement of the stars across the sky determined human fates, and Mayan priests kept constant watch of the sky. They discovered the connections between the seasons and the changing positions of the stars. They determined the length of the tropical and synodic years and the lunar cycle—the duration of a month. Out of this knowledge the Mayas developed their incredibly accurate calendar, which not only completely dominated the lives of individuals but at a certain moment induced the whole people to tear up their roots and leave the land.

Although ancient philosophical systems did contain elements of dialectics and rested on fairly extensive knowledge, they were nevertheless extremely naive. The philosophers of ancient Greece, however, evolved a much deeper and more consistent understanding of the world, which is why ancient physics is almost exclusively Greek physics. The Indians, Chaldeans and Egyptians never developed a science of nature. Their mystical religious beliefs were incapable of producing ideas about the nature laws governing various phenomena. Science originated when men who analysed and classified experience began to seek the explanations of nature within nature itself.

Thales of Miletus (640-550 B.C.) is credited with being the first Greek physicist, one of the seven "wise men" of ancient Greece. At an advanced age he sailed aboard a Phoenician ship to Egypt to learn the secrets of the priests of the ibis-headed god Thoth. He lived a long life but never knew peace of mind. The variety and changeability of the world drove him to seek the fundamental principle, or element, of things. In effect he set himself a task in many ways resembling that facing physicists at Dubna or Berkeley today. History has preserved a postulate attributed to Thales: "Water is the principle, or element, of things; all things originate from water and all things revert to water."

Thales is credited with being familiar with the mysterious force of the magnet and the attraction of light bodies by electrified amber. He is said to have divided the firmament into five orbs, discovered the ecliptic, held that the earth is a sphere and calculated the apparent size of the moon.

There are no extant works of Thales or his disciples. Obviously the sage of Miletus could not have appeared out of nothing, he must have had predecessors and teachers, but time has withheld their names.

After Thales the Ionian school was headed by Anaximander (610-547 B.C.), also of Miletus. His teaching is more complex and subtle and bears elements of the strangeness that has persisted through the centuries to the present day.

Anaximander held that the origin of everything was a primary mass, indefinite and eternal, from which the primary opposites of heat and cold, dryness and moisture separated. All this hypothesis lacked was a mathematical apparatus and thirty centuries of empirical knowledge, in which case it would have been hardly inferior to Werner Heisenberg's primary mass. This is putting it jokingly, of course, but the idea of primary matter is worth pondering. What force of scientific abstraction one had to have to visualize a single metamorphic principle as the basis of all things! Nowadays the expression "a mad idea" has become a cliche. But was not Anaximander's idea "mad" in an age when heat and cold were regarded as absolute opposites?

Another successor of Thales, Anaximenes, introduced the dynamic principle into the theory of the structure of matter,

to use contemporary terminology. He held that air is the primary substance. It is the source of all that exists. When air contracts it becomes water, and water becomes earth. When it expands it yields fire. All living creatures are sustained by air and must sooner or later return to air. Needless to say Anaximenes did not anticipate the idea of liquefaction of gases or solidification of liquids. The teachings of the ancients were so general and vague that one can easily fit any meaning into them. Let us, therefore, not exaggerate the knowledge of the ancient natural philosophers. We are concerned with what the philosophers of the Ionian school shared in common. Their teachings are based on the concept of a single primary substance which metamorphosed into all other substances, producing the whole visible world. The genetic connection with modern unified field concepts is apparent. Modern science is certainly radical, sudden and coloured with strangeness and "madness" (in Bohr's sense of the word) but this does not mean that it negates all of man's age-old experience. On the contrary, in a sense it is rather traditional, and nor could it be otherwise, whatever people might say. Science does not negate itself. Today we can see how beautifully Newton's mechanics and Galileo's relativity principle fit into the theory of relativity.

Pythagoras of Samos (582-500 B.C.) is considered to have been a disciple of either Thales or Anaximander. In any case, he apparently knew them both. He visited Egypt and, it is said, Babylonia. After a long stay with Egyptian and Chaldean priests, Pythagoras returned to his native land and settled at Croton, where he founded a school and a secret philosophico-political brotherhood or association. Those who wished to join the society were subjected to protracted rigid tests. An applicant could prove his ability for self-denial only by maintaining a five-year silence. Judging by the speed with which the society expanded the severity of the tests tended rather to attract young people than to discourage them. Soon the Pythagorean society acquired considerable power over Croton and other cities. This, not unnaturally, gave rise to hostility and unrest. The school was destroyed and Pythagoras himself was killed in the fray.

The mystery that shrouded the society's activities clings to it to this day. Although the theorem that bears Pytha-

goras' name has been suggested as a key for establishing contacts with extraterrestrial civilizations, we know very little about his teachings. Judging from fragmentary information that has reached us from latter-day sources, the Pythagoreans' main concern was not so much with some primary substance as with the distribution of things in nature, with their numbers and measure. Aristotle tells us that the Pythagoreans sought analogues of things and events not so much in elements such as fire, earth or water as in abstract numbers. They supposed the elements of numbers to be the elements of all things. Accordingly, they sought numerical laws in all things, even to the extent of forcing the surrounding world to conform to their postulates. These also made them ascribe sets of opposites (good and evil, finite and infinite, etc.) to numbers themselves. A modern scholar would have said that the Pythagoreans had encountered mathematical difficulties. To be sure, mathematical ideas frequently yield paradoxes, but they also contain a basis for further advance. Pythagoras, however, had chosen a mistaken road which led to a mystical science of numbers that subsequently merged with astrology and as such survived late into the Middle Ages.

It is said nowadays that the scientific value of a theory is in direct proportion to the mathematics it contains. The mathematical theories of Pythagoras did not enrich science much, for they were rendered obscure by mysticism.

There are extant fragments of a manuscript by one of Pythagoras' favourite pupils, Philolaus (470-399 B.C.). The Pythagoreans, it is known, were the first to postulate that the earth is a sphere. They did not proceed from empirical data in putting forward this, for those times, quite "mad" proposition. The idea was no more than a concession to beauty and symmetry and was rooted in the requirements of geometrical harmony. In their quest for perfection in the creation the Pythagoreans ascribed the earth the most perfect shape. It is interesting to compare this statement of Philolaus with present-day arguments in support of the existence of quarks. When the reader gets to that part of the book he will feel the common methodological features of the Pythagoreans' approach and the modern physical hypothesis.

At the centre of the universe the Pythagoreans placed the purest of all substances, fire. At harmonious distances

from it revolve the counterearth, the moon, the sun, Mercury, Venus, Mars, Jupiter, Saturn and the sphere of the fixed stars. The counterearth and central fire are not seen by us because the hemisphere we inhabit is always turned away from them. The sun and moon, however, reflect the life-giving light of the central fire onto the earth.

The Pythagoreans have been accused of inventing the counterearth for the sole purpose of bringing the number of world spheres to ten, as required by mystical science. There is, however, one consideration which would seem to suggest that they had more serious grounds for creating the counterearth. The thing is that in so-called horizontal eclipses the sun and occult moon are seen as lying opposite each other, a position which makes it necessary to introduce refraction to explain how the eclipse takes place. It is possible that the Pythagoreans introduced the central fire and counterearth to explain the eclipses. Such an introduction of *ad hoc* elements into a theory is a justified scientific procedure frequently employed in physics.

The third of the ancient Greek philosophical schools, the Eleatic, was opposed to the Ionian doctrine of development. It saw nature as a universal, immutable unity, regarding creation and variety as illusions of the senses. It is interesting to trace the Eleatic influence on later so-called young natural philosophers who, unlike the Ionians, accepted the immutability of primary substance and, unlike the Eleatics, the multiplicity of world elements. This is a new dialectical development in the history of science in which a new school imbibes all of the best from two opposing older systems.

Anaxagoras (500-428 B.C.) is generally regarded as the first of the young natural philosophers. His quest for knowledge drove him from his native Lydia to Athens. Several years later he could claim, with good reason: "Philosophy has brought me material destitution, but spiritual affluence." Among his pupils we find such celebrated men of ancient Greece as Pericles, Euripides and Socrates. It is hardly surprising that such a man should have aroused not only the love and esteem of his contemporaries but their envy and hostility as well. He was accused of godlessness and sentenced to death. Only the intervention of Pericles aved his life. He went into banishment, comforting himelf with the thought: "It is not I who have lost the Athe-

nians, but the Athenians who have lost me." A statue of him bears the bold statement: "Here lies Anaxagoras, who attained the farthest limits of the truth and discovered the structure of the universe."

Many generations have passed since then, and every one of them has made it its duty to claim that one of its representatives had attained the farthest limits of the truth and discovered the structure of the universe. Our age is no exception, though nowadays, perhaps, the limits of ultimate truths are challenged more frequently than before. Today we are armed with materialist dialectics which encompasses the teaching of relative and absolute truths. Only in the light of this teaching can we truly judge the contributions of Greek natural philosophy to world culture according to its merits.

There are several extant fragments of Anaxagoras' main work, *On Nature*. Anaxagoras held that the substance of things is not affected by apparent changes of the things themselves; these are due to the combining and separation of infinitesimally small fragments of matter.

Books on atomic physics usually start out with Democritus and his atoms. Yet his theory was no more than an expansion of the ideas of Anaxagoras. More, Anaxagoras even anticipated by many centuries the law of conservation of mass, one of the cornerstones of contemporary natural science. It is worth quoting from his work:

"The Greeks mistakenly hold that things come into being and pass from it; but nothing appears and nothing disappears, and change is no more than the aggregation or disruption of things existing eternally. It would be more correct to say that creation is aggregation and decease is disruption."

In actual fact, of course, Anaxagoras' philosophy is not all that clear and prophetic as it may appear at first glance. One should not forget that we are judging it from present-day standards. Especially as at the bottom of his teaching lay the concept of some universal intelligence. At the beginning the universe was a chaos of elements; the infinitesimal particles were then arranged by a Mind or Reason. This intelligence is contraposed to matter—and is thus related to the countless modifications of the "world spirit" which have been passing from one idealistic teaching to another for more than two thousand years.

Here is an interesting excerpt from Plato's *Phaedo*:

"I once listened to a man reading a book written, he said, by Anaxagoras. When he read that mind is the cause of all order and structure, I was gratified by this explanation and happy to accept mind as the cause of all things. So I thought, and was prepared to hail Anaxagoras as a teacher capable of explaining the meaning of things; that, firstly, he would tell me whether the earth is flat or a globe, and that he would prove that it is so, stating the postulate according to which it is best for the earth to have this shape. And that if he said it lay at the centre he would prove that this position is the most expeditious. In this case I would have had to seek no other cause. However, my friend, I was compelled to part with this pleasing hope when further reading revealed that Anaxagoras makes no recourse to mind, nor does he indicate the true cause of all order and structure but, on the contrary, recognizes air, ether, water and many other unsuitable things as the cause of all things."

Anaxagoras' opponent makes his point. His requirements to the new theory are clear and justified. He requires harmony, reciprocal causality of phenomena, motivation of causation, and noncontradiction of effects. All of which are criteria of our day.

The Eleatics were probably the first who realized that truth is by no means self-evident and common sense is no measure of the validity of scientific theories. Anaxagoras was well aware of the fallibility of our senses, and he ascribed the colours of bodies only to our sensations; to make his point clearer he frequently resorted to paradoxes, such as "snow is black".

Anaxagoras' ideas were formulated more precisely in the teaching of Empedocles (492-432 B.C.). Like his teacher, he wrote a book entitled *On Nature*, in which he sets forth his credo: "Crazy people think that things which did not exist can come into being and that existing things can perish and vanish without trace. I shall attempt to show you the truth. In nature nothing comes into being which can decease; nothing is entirely destroyed; there is nothing but the agglomeration and separation of agglomerates. Only fools call this birth or death." Very much like Anaxagoras, isn't it? The surprising thing is that it can be applied, for example, to the transmutation of elementary particles. All the

more so as Empedocles, unlike his predecessor, replaces an infinite number of primary elements by only four—earth, water, air, fire, that is the three states of matter, and energy. It is tempting to interpret this theory as postulating that the states of matter can change one into another through the agency of fire. However, it has nothing to do with Empedocles' system, and the same, incidentally, can be said of other attempts to explain the concepts of the ancients from the standpoint of the present. Empedocles' elements, or "roots", are immutable and incapable of developing one out of the other. They are motivated by two opposing essences, love and strife. "Now the force of love draws things together, now the whole is separated through implacable strife." This is spontaneous dialectics, a vague premonition of the truth yet to be achieved through logical constructions. Some researchers were inclined to see Empedocles' love and strife as centripetal and centrifugal forces. But this is as arbitrary a deduction as the claim that Anaxagoras had formulated the law of conservation of mass. It required not only Lavoisier's scales but a radical breaking up of scientific conceptions for the law to be both formulated and accepted.

History knows of many truths voiced long before their time. They have always had to experience a second birth.

Very little is known of Empedocles' life. If we are to believe Horace, he calmly threw himself into the funnel of Etna to show that he was a god and an immortal. The volcano, however, tossed his iron sandals back, indicating that a mere mortal had died. But time has preserved his work, and Empedocles has gained immortality in the memory of generations.

Democritus of Abdera (460-370 or 360 B.C.) and his teacher Leucippus are usually mentioned together. Leucippus first enunciated his atomistic theory of the world in circa 500 B.C. Subsequently it was developed and completed by Democritus. The universe of Democritus and Leucippus comprises the void and an infinite number of minute indivisible particles—atoms. The atoms do not differ in quality, as postulated by Anaxagoras, but only in configuration, position and arrangement. Bodies appear or disappear only in the combinations or separations of atoms (remember Anaxagoras and Empedocles): nothing can arise out of nothing; nothing can be reduced to nothing. The motions of the

atoms are due not to any mysterious external force but to one inherent in the atoms themselves.

Any modern physicist would readily undersign this general scheme of things. But, unlike Democritus, he would also be able to prove that that is just how the world works. A small difference, it might appear, yet behind it lie centuries of toil and struggle, the imposing edifice of modern science erected brick by brick.

But Democritus goes farther and seeks to expand his purely qualitative formula. His atoms are in a state of continuous fall in infinite space. The larger atoms fall faster than the smaller (Democritus did not know that in vacuum all bodies fall with the same speed; this experiment was to be performed only two millennia later), collide with them and take part in lateral and whirling motions whereby the atoms are brought together to form larger bodies. One can sense here a subtle analogy with ancient Indian philosophy and the first serious cosmological constructions of later centuries.

More than any other philosopher of antiquity Democritus is presented as something of an augur who made nature reveal the essence of things independently of phenomena, simply by the force of his great powers of abstraction. At best this is an exaggeration. Human knowledge gets to the essence of things only through an understanding of phenomena. And if one carefully studies ancient atomistics one will find that in many ways Democritus' teaching is quite traditional. The appeal and modern appearance of ancient atomistics are due primarily to the vagueness of the definitions. Take Democritus' understanding of vacuum. Here is his proof of the existence of the void: "For if the void did not exist, movement through space, rarefaction and condensation of bodies, the growth of bodies, which takes place due to the penetration of stuff into spaces, would be impossible." Finally, among his proofs (and this is most interesting to us) there is a direct, and a completely erroneous, empirical observation: a glass filled with ash can receive a smaller volume of water than space without ash. This mistake of the great philosopher is as valuable to us as his foresight. It demonstrates that the ancients got to the truth not through revelations but in much the same way as we. And we are justified in tracing the history of human thought as a continuous, successive process.

FOUR ELEMENTS, BUT ONLY ONE GENIUS

The physical ideas of Plato (429-347 B.C.) are as fantastic as the myth of Atlantis, but they lack the naïveté and charming poetry of the accounts of the Golden Island. Plato's cosmogony is sterile and scholastic. At the centre of the Universe sits a motionless Earth around which the planets swim at distances standing in harmonious ratios. The elements of fire are all proper geometric tetrahedrons, those of air are octahedrons, of water, icosahedrons, and of earth, hexahedrons. Corresponding to these elements are four principles, from the heaviest, earth, to the lightest, fire. Each principle seeks to occupy its place and all bodies obey the dominating principle in them: stones fall to earth, fire ascends to the stars.

A remarkably uncosy, one could even say bureaucratic system. Small wonder medieval dogmatists embraced it so readily. The fate of ideas is worth tracing. Formal, ossified systems have frequently persisted on the historic scene much longer than productive, revolutionary teachings. This is understandable. The former became havens of stagnant conservatism while the latter served true knowledge, and therefore sooner or later revealed their inner fallacies—but this is the prime mover of progress!

Of Plato's pupils, most interesting to us is Eudoxus of Cnidus (408-355 B.C.) who put forward an interesting hypothesis to explain the observed irregularities of planetary motions.

The Ionians and Pythagoreans had ascribed each planet a hollow sphere along which it followed its path around the Earth. These spheres, however, failed to explain the various irregularities of planetary paths. Representatives of both schools stubbornly insisted that celestial bodies could have only uniform circular motion, the only type of motion worthy of the heavens. But the planets insisted on moving erratically, sometimes faster and sometimes slower, and this had to be reckoned with. Plato suggested that Eudoxus work out an explanation of the observed motions in an effort to remove every trace of nature's capriciousness from the cold, harmonious system. Eudoxus coped with the task brilliantly. He postulated that each planet was fixed to a transparent spherical shell (one can't help marvelling at man's ingenuity coupled with the uncompromising logic

of abstract thinking!) capable of rotating on an axis inside another spherical shell, and so on. Each sphere rotates on its axis uniformly in the prescribed direction. The aggregate of these rotations produces the irregularities observed in planetary motions. Each planet requires four spheres: one for its diurnal motion together with the fixed stars, one for changes in longitude, one for changes in latitude, and one to account for retrograde motion. The sun and moon required only three shells as they never displayed retrograde motion.

Today we may well smile at all this, but in its time Eudoxus' hypothesis must have seemed as beautiful as Kepler's mechanics or Maxwell's electrodynamics. It contained all the necessary elements of a theory summing up and explaining known phenomena. Small wonder that Aristotle adopted it in toto, with certain amendments and adjustments. Thus, Eudoxus needed 26 spheres; Aristotle increased this number to 55.

Aristotle (384-322 B.C.) was born in the northern town of Stagira on the Aegean Sea and died on the island of Euboea whither he had fled after being accused by the anti-Macedonian party of offending the gods. A truly classical accusation and classical fate for a scholar! But let us have a look at Aristotle's teaching. As opposed to Democritus, who held that matter is discrete, Aristotle postulated its continuity. This great debate has been going on throughout the history of natural science and, as we shall see later, continues to this day.

Aristotle's *Nature* is a totality of physical bodies made up of matter which are in a state of continuous movement or change. Movement, naturally, takes place in time and space. Aristotle's space is pervaded throughout with matter, leaving no place for the void or infinitesimal indivisible particles (atoms) falling infinitely in it. Void, according to Aristotle, is a negation of matter, which makes it impossible to define or distinguish places. But movement presumes that places can be distinguished, hence in the void movement is impossible.

Underlying all tangible bodies is a primary matter-stuff on which four fundamental qualities—wetness, dryness, hotness and coldness—can be impressed. The diversity of substances in nature is due to different combinations of these qualities. The basic elements—earth, water, fire,

air—are combinations of two of the basic qualities. For instance, the combination of dryness with cold gives earth; the combination of coldness with wetness gives water; heat with dryness gives fire, and with wetness air.

Transmutations of matter are caused by changes in the combinations of qualities. If the coldness of water is overcome by heat, the water changes to steam or air. Reversibly, coldness impressed on air causes it to condense into mist, which precipitates on rocks as water. Dryness added to water turns it into earth.

From here it is but one step to the notion that all metals are analogous in composition and, hence, can be transmuted into one another; notably, base metals can be turned into gold. Latter-year alchemists frequently made reference to Aristotle. In our nuclear age we know that in essence he was right. However, no amount of justification from the heights of new spirals in the advance of science can salvage erroneous theories. Aristotle or Paracelsus would have been right today, but in their time they were mistaken.

Aristotle's elements, or principles, are inseparable from motion. The elements are, according to their nature, either light or heavy. Earth is absolutely heavy, fire is absolutely light, air and water are relatively light or heavy, depending on their combinations with other elements. Hence, all earthly bodies possess inherent lightness or heaviness and therefore tend either to the ground or to the sky. Upward and downward movement is natural to all bodies and ceases only when forcibly halted. Any other movement is forced, induced by impact or pressure: like heat, once its cause is removed it ceases spontaneously. Natural rectilinear movement of bodies is nonuniform and finite, hence imperfect. Only circular movement is perfect and eternal. Its immediate cause is the ether, the fifth essence—*quinta essentia*—which constitutes the sky. Naturally, the uniformly moving sphere of fixed stars is made up solely of the ether. The planetary spheres, on the other hand, contain mundane essences, which is why their motions are so imperfect.

The ether concept was to persist in physics for a long time to come. It would be perfected and evolve, but its essence would remain the same: unchangeable and intangible as the ether itself.

Aristotle was much more of a philosopher than a phy-

sicist, for his purpose was to evolve a comprehensive picture of nature. With one broad sweep he sought to embrace the whole universe, and he hoped to achieve this by the method of pure speculative reasoning. Centuries later science adopted the diametrically opposed method of wingless empiricism. Only in recent times have men realized the great unity of these opposites and understood the dialectics of knowledge. Aristotle is great for his attempt to fathom the overall unity of the world. However, he neglected particulars in the process, something even a great scholar cannot do with impunity. Physical theories cannot advance without precise measurements. Rarely can a scholar evolve even a purely qualitative picture of a phenomenon or process and expect it to be valid without bringing in quantitative laws. Let us take an excerpt from Aristotle's *Physics*.

"Boiling water warms more than fire, but fire burns the combustible and melts the fusible, while water does not. Furthermore boiling water is hotter than weak fire, but warm water cools faster than weak fire, because fire does not lose heat, whereas water cools gradually. In addition, boiling water is hotter to the touch, but it cools and solidifies faster than oil. Blood is warmer than water or oil to the touch, but it solidifies faster than either. Rocks, iron and so on warm slower than water, but once warmed they are hotter to the touch. Moreover, some so-called warm bodies contain external heat while to others it is intrinsic. There is, however, a great difference between different types of heat. One body possesses heat fortuitously, not according to its nature, it is as though, if a patient suffering from fever happens to be a musician, someone would say that musicians are warmer than men with healthy heat. If one body possesses intrinsic heat and the other is warmed, the former cools slower, while the latter is warmer to the touch. On the other hand, a body possessing intrinsic heat burns stronger: for example, fire burns the skin worse than boiling water, although boiling water, which possesses induced heat, is hotter to the touch. Thus it is by no means easy to say which of two bodies possesses more heat, as in one way one body proves warmer than another, while in another way the other proves warmer."

This discourse would have been of any value if Aristotle had had a criterion of heat. But with only qualitative characteristics, even a great scientist can achieve lit-

tle. Imagine a physicist trying to classify elementary particles without any knowledge of their masses, charges and spins. He would hardly have achieved more than Aristotle.

However, on more abstract questions lying at the boundary of physics and philosophy Aristotle's statements are to this day quite remarkable. Here, for example, is his definition of movement: "Movement is the implementation of the existing in the possible. It is the action of the moving body with relation to its mobility." Movement, according to Aristotle, comprises five principles: the cause of movement, that which moves, the direction of movement, the initial point, and the destination. To a degree the destination determines the nature of the motion. Movement is inseparable from change in quantity, quality and place.

With Aristotle ends the creative, as it is sometimes called, period of Greek natural philosophy. It was a self-contained, closed system which resisted further development. Besides, the prestige of Aristotle was so great that few people ventured to reassess his teaching.

THE DOWNWARD ROAD

In some ways the post-Aristotelian period resembles the nineteenth century, when it seemed to many that physics had exhausted itself and become an absolute truth. Aristotle's immediate followers, Eudemas and Theophrastus, still timidly ventured to develop his teaching, but soon the Aristotelian system was canonized and no one dared encroach on it. To be sure, alongside the interpreters of the great thinker from the Peripathetic school who explained the world from theleological positions in terms of ultimate goals and aspirations to perfection, there were atomists who pursued their teaching, but even such a fine atomist as Epicurus (341-270 B.C.) followed so faithfully in the steps of his god, Democritus, that his physics can safely be described as Democritean.

The period from circa 300 B.C. to A.D. 150 is regarded as the period of antique mathematical physics. The inscription over the gate of the Plato's Academy, "None ignorant in mathematics may enter this building", could well be applied to all science of the time. And yet, with

the sole exception of Euclid, who created the formal apparatus of geometry, not a single ancient Greek physicist contributed anything essential to the concepts of space, time or matter. However, there were some isolated advances. Aristarchus of Samos taught that the earth revolved around the motionless sun. To the objection that in that case the fixed stars should also change their apparent positions he rightly pointed out to the vast distance to them from the sun. In this respect he was a forerunner, not only of Copernicus, but of Einstein as well, for what he did was to rebel against "common sense". But the heliocentric system still had no firm foundation and was too far in advance of its time. The appeal of geocentrism was so great that none of the best astronomers of the time supported Aristarchus. His teaching was well forgotten, and Copernicus had to rediscover heliocentrism all over again. Truth has always found its creator when its time came.

The great works of Archimedes laid the foundations of experimental physics. He is justifiably regarded as the father of physics.

An annual carnival at Moscow University's Physics Department celebrates the holiday of Archimedes. At the first of these celebrations the author rode for a while in a power truck along with Archimedes himself and with Lev Landau. Behind walked Roentgen, Gibbs, Fermi and other celebrated physicists. All of them, with the exception of Landau, were, of course, students in disguise, but each carried his marshal's baton in his rucksack.

I have not the slightest intention of encroaching on the prestige of the father of physics, but since his work has no relation to the fundamental problems set forth in this book we must, with profound regret, pass it by.

The same goes for Eratosthenes, who determined the size of the earth fairly accurately, and for Cleomedes, author of *The Cyclic Theory of Meteors*. And although Ctesibius and Hero of Alexandria did much more for the advance of physics as an experimental science than the poet Titus Lucretius Carus, mention must be made of the latter's didactic poem, *De Rerum Natura* (On the Nature of Things).

In present-day terms Lucretius was a popularizer of science. Nevertheless, his contributions to the advance of atomistics can hardly be overestimated. Perhaps this is due to the power of art, to its conventions, so different from

scientific abstractions and analogues, but in all epochs Lucretius sounds equally contemporary

.... A garment will always get moist, but hung in the sun it will dry,
Though none ever have seen how water settles on it,
Or the manner in which it dissolves in the heat.
Therefore water breaks up into such minute particles
That they remain unseen to our eye.

It is hard to believe that these words were written two thousand years ago.

Lucretius, to be sure, added little to the teachings of Democritus. And still, our reference to him is not without reason. The small excerpt from his poem tells us not so much *what* the ancients thought as *how* they thought. It is an example of clear logic leading to an unequivocal conclusion.

Another extremely interesting passage in *De Rerum Natura* deals with magnetism.

All bodies continuously emit streams of atoms, through which they interact. The streams emitting from the magnet are so strong that they create an empty space toward which the iron moves. Only iron is drawn by a magnet. Other bodies react differently: heavy bodies resist the magnetic flux by their mass, light ones are filled with holes and the streams of particles pass through them.

This example shows how typical it was of latter-day natural philosophy to support one hypothesis with other more vague ones. The methodology was characteristic of scholars of virtually all schools. Hypotheses were piled up one on top of the other until the whole system collapsed like a house of cards. And no attempt was made to verify even a single hypothesis by experiment.

Ideas evolve along tortuous, often contradictory paths, and their sources and embodiments frequently defy tracing. By analogy with the field theory we could say that it is like a quantum process. Not every idea has a historical path. An idea may die and be reborn again without any apparent links of succession between the two acts. We sometimes find analogies between ancient and modern science, but as often as not they may be purely fortuitous. On the

other hand, a closer inspection may reveal some connection between a hypothesis of the hoary past and a modern theory where no apparent similarity strikes the eye. Those who claimed that science always burns its bridges were, after all, in the wrong. They simply failed to notice that a small footbridge was replaced by a huge bridge joining the shores with a single span.

With Ptolemy (A.D. 70-147) ends the ancient period in the history of natural science. His authority was accepted universally and survived the longest. He was equally revered by Greeks, Romans, Arabs and Christians. Many a heretic perished at the stake for challenging the truth of his *Almagest*. For several centuries the Catholic church upheld Ptolemy's teaching with all the means at its disposal. Ptolemy had assembled and summed up all the achievements of ancient astronomy in thirteen volumes. But despite the endeavours of its founder, Ptolemy's system of the world, with a fixed Earth at the centre of the universe, hardly enriched science. It was much too complex. "It is simpler, it seems, to move the planets themselves than to understand their complex motions," Ptolemy wrote. Ultimately it was this complexity that blew up his teaching from the inside. In modern times Ptolemy has even been denied credit for the system of the world that bears his name, the idea being ascribed to Hipparchus.

The period from A.D. 150 to 700 is seen as the decline of ancient physics. The free critical spirit of Hellenic natural philosophy was replaced by the mysticism of Plotinus and Lactantius Firmianus. Wrote the latter:

"Can people be so foolish as to believe that, at the other side of the Earth, corn and trees grow upside down and people walk with their feet over their heads?" Thus did "common sense" seek to erode the shoots of relativism from natural philosophy. In a way this is reminiscent of the attacks of "Aryan" physics against relativity theory in the years of Nazism. The level of argumentation, at least, is very similar.

ON THE FUNDAMENTALS OF ALCHEMY AND THE HARM OF DEIFICATION

Following the expulsion of the last philosophers of the Athenian school by the Byzantine Emperor Justinian a

reign of darkness and silence ensued, in the words of one chronicler. It seemed that the torch kindled by the thinkers of Greece had gone out. The light of learning, however, was carried aloft by the Arabs, and the period from A.D. 700 to 1150 is known as the period of Arab physics. The Arabs accepted Aristotle's philosophy in toto, making virtually a semigod of him. Mathematics, astronomy and medicine flourished abundantly at the courts of caliphs. But the Arab scholars hardly touched upon the fundamentals of the universe, remaining prisoners to Aristotelian conceptions which, furthermore, had by then lost their initial creative and restless spirit.

The first outstanding Arab chemist was Abu Musa Jabir, or Geber as he is traditionally called. He lived around the year 800 and remained the supreme authority among Arab and European scholars into the 15th century. He was the Aristotle of chemistry, whom Roger Bacon called Magister Magistrorum.

The Greeks had hardly studied chemistry. Geber's knowledge in the field was truly remarkable; moreover, he undertook to formulate the first chemical theory.

Geber held that all metals are composed of two principles resembling mercury and sulphur. When a metal burns it loses sulphur, the combustible principle and source of combustion.

Later medieval chemists who accepted Geber's theory were more concerned, not with combustion, but with transmutation, for it seemed obvious that, if all metals are made up of the same principles, by changing their proportions one could, evidently, change one metal into another—lead into gold, for instance. For this reason Geber is regarded as the father of both chemistry and alchemy. Especially as his disciples followed the latter road. The idea of turning one metal into another was too tempting to resist.

Thus, the logic of our topic leads into the dismal cellar of the medieval alchemist.

"One cannot claim to have knowledge of science without knowledge of its history," writes Albert Poisson. "From the first idea that engendered it to the present time—what ceaseless effort, what groping in the dark! We light-heartedly use our predecessors' works without stopping to consider the tremendous amount of physical labour put into them to clear the road for us. How many of them ruined

their health, spent their fortunes and spurned honours and pleasure in the name of their passion for knowledge! How many of them died martyrs, upholding the eternal truth to their last breath!"

These fine words could be applied to the thousands of nameless alchemists who gave their lives for illusive hope. Consciously or otherwise, they too contributed to the great process of knowledge, they too sought the primary essence of things.

The medieval alchemists placed the beginnings of their science in the times of mythical Atlantis. It was in the mysterious shrines of that lost land that the search had begun for a means of turning base metal into gold and silver. Orthodox tradition, however, ascribes the development of the art of turning things into gold to the Egyptian priest Hermes Trismegistos ("The thrice greatest Hermes") credited with the authorship of 42 legendary learned treatises. In the Middle Ages some alchemist compiled a paper which later became known as the *Emerald Table of Hermes*. This curious fake is worth quoting, especially as it is not deprived of a certain poetry.

"So be it, veritably, truly and justly!

"That lying beneath is that lying above, and that lying above is that lying beneath, for the purpose of working miracles of one and the same. And as all things derive from one, at the will of the One, so they all derive from that substance, through its application.

"His father is the Sun, his mother is the Moon, the Wind carried him in its womb, the Earth has suckled him. His power on Earth is without limit.

"Carefully, with utmost skill, separate earth from fire, the fine from the coarse. The substance ascends from earth to the sky, only to descend at once back to the earth. It absorbs the strength of the things above and below.

"And you shall obtain the glory of the world, and darkness will flee.

"This is the mighty force of every force, it will catch the ellusive and permeate the unpermeable, for thus has the world been created!

"This is the source of wonderful applications .... This is why I have been called Hermes Trismegistos, master of the three chapters of Universal philosophy. All I have said here pertains to the Sun."

The Sun is, of course, gold. What a long, long retreat from Aristotle or Geber had to take place for such a recipe to be produced. Mysticism, return to savagery, neglect of facts—alas, all this, too, characterizes the development of science. As we shall see later on, attempts to smother genuine knowledge were undertaken even in the 20th century. We have, in fact, lived at the same time as men who had attempted to resurrect the gloomy, barren spirit of the Middle Ages. That is why the history of mistakes is as important as that of the quest for truth. We must know who, and how, sought to lead knowledge into a dead end.

At its grass roots alchemy was not a false science. Today, when men have learned to synthesize elements not found in nature, we can appreciate this more clearly. Alchemy cannot be ranked alongside astrology or black magic. As long as the Arabs were engaged in mixing and separating substances in an attempt to turn lead into gold by chemical methods they remained genuine scientists. It was only when alchemists began searching for the philosopher's stone, the red elixir and other such sources of perfection that they became quacks. Whether they willed or not. There could be no compromise here. Alchemists substituted fantasies for scientific quest and crystal-gazing for logical analysis. That is why it would be wrong to belittle the harmful influence alchemy has had on the development of natural science. But neither should we fall into the other extreme. Alchemy started out not with theories but with experiments and over the centuries it accumulated a wealth of facts. Besides, as often as not a camouflage of black magic was rigged about alchemic doctrines to mislead outsiders concerning specific chemical reactions which could be easily reproduced.

Take the pictures in old books on alchemy. At first glance they are grim grotesque—skeletons, ravens, torches—all the mystical trappings. But many of them are easily deciphered as nothing more mysterious than symbols of chemical processes of distilling, decomposition, etc. For example, the action of fire produces a charred black skeleton of a substance (ash) and a bird (volatile gas). Basically this is a primary chemical symbolism, a language for recording chemical reactions.

The celebrated French nuclear physicist Bergier, a great specialist in ancient sciences, has unraveled the true meaning of many alchemic operations which at first glance ap-

pear to be pure black magic. Notably, he regards alchemic prayers and invocations as a means of measuring time in a dark laboratory. A clever interpretation. Perhaps originally this was the case, but as it passed from generation to generation this mode of "measuring time" eventually turned into plain hocus-pocus.

One cannot, of course, totally deny the contribution of alchemy to world culture. But one thing should be made clear. Random trial-and-error tests of all possible chemical combinations have nothing in common with scientific experimental methodology. In the same way, "modern alchemy" has nothing in common with classical alchemy. All that links contemporary nuclear physics with the age-old attempts to "make gold" is the concept of a common matter underlying all substances. But then, the alchemists were not the first to expound the idea. They inherited it from Greek natural philosophy. Modern science is not a continuation of alchemy. They are two streams rising from a common source. One degenerated into a quagmire, the other has expanded into a great river flowing into a boundless ocean.

The Arabs achieved much in astronomy, geodesy, optics. For example, measurements made by Alhazen in the 11th century are wonderful for their accuracy. Here are several examples from Alhazen's table of specific weights, with present-day data in parenthesis: foundry gold, 19.05 (19.3); mercury, 13.56 (13.545 at 20°C); lead, 11.32 (11.34); silver, 10.30 (10.445); copper, 8.66 (8.89); iron, 7.74 (7.88); pearl, 2.60 (2.684); ivory, 1.64 (1.825-1.917); boiling water, 0.958 (0.95835).

These figures speak for themselves. The Greeks knew nothing of the kind. But despite the vast empirical foundations they created, Arab scholars failed to advance any new philosophical notions concerning the structure of the world. Even such an eminent scholar as Averroes (Ibn-Roshd) is remembered only as a profound admirer and commentator of Aristotle.

"Aristotle is the beginning and end of all sciences. No writer worthy of mention preceded him, and for fifteen centuries since him no one has contributed anything outstanding to his teaching or pointed out any errors in it. Aristotle is the greatest of men. God permitted him to attain the acme of perfection."

With such an attitude toward the precursors, one can hardly expect any development or perfection of the world picture. There is nothing more hostile to the very idea of science than canonization of teachings and deification of teachers. Such attitudes have yielded no good in other fields of human endeavour as well. Yet they recur again and again, which is why the subject continues to merit attention. They are as harmful as nihilistic negation of all that has been accumulated in the past. You can't build something on nothing, but neither can you build something if you are burdened with the conviction that everything worthwhile has long since been created. The purpose and meaning of human activity is to forge ahead. That is why it is always necessary to subject all that has been created before to a strict and thrifty re-evaluation.

The theory of relativity has been brilliantly confirmed. It is a cornerstone of modern natural science. Yet people in laboratories all over the world persist in staging experiments aimed at refuting the theory. Occasionally articles claiming success appear, though so far they have been quickly followed by other articles pointing out fundamental errors. Are such apparently barren works of any use? Strange as it may seem, yes. A scientific theory cannot be made into a religious dogma. Dogmas fear the test or doubt. Genuine science does not. But if a ban were to be imposed (as if anything in science can be banned or authorized!) on attempts to verify the relativity theory the temptation might appear to extend such a ban to other, far from sterile attempts to verify this or that notion.

Let the eccentrics continue to refute the relativity theory—if only for the sake of preserving a strong critical spirit in science.

THE DARKNESS DEEPENS BEFORE THE DAWN, BUT IT ALSO PALES BEFORE THE DAWN

Slowly, little by little, dormant thought began to awaken in the quiet of monastic cells of medieval Europe. Interest developed in the writings of the Greek philosophers. It was then that the famous ontological proof of God's existence was put forward: God is that Being than whom none greater can be conceived; if that be the case, then God necessarily has real existence, for otherwise He would not be the greatest.

Such is the logic of progress that the church, in defending its existence, dealt itself a mortal blow. As it set out to prove the existence of God it had to appeal, not only to the emotions, but to the intellect as well. But this is a chain reaction. The intellect refuses to be satisfied with the dictum of St. Anselm, Archbishop of Canterbury: *Credo ut intelligam* (I believe so as to understand). Rather, it wishes to understand so as to believe—or, perhaps, disbelieve?

Appealing to the intellect revenges itself, for proving a point demands recourse to strict logic, and polemic requires elements of dialectics. So it became necessary to turn to the teachings of ancient philosophers; the purpose was to set religious dogmas on rational foundations and have thinking people accept faith as a code of knowledge and dogma as a criterion of research.

"Let each man believe unswervingly, love his faith and live in concord with it, and let him seek the foundations of his truth in humility. If he is capable of perceiving it, let him praise God; if not, may he not rebel against the truth, but bow his head in worship." Eons of time lie between these words of Anselm and the teaching of Epicurus. Mankind seems to have been thrown irreversibly back. But the crack in the church's teaching is filled with powder. A spark is sufficient for the whole age-old ecclesiastical edifice to be blown sky-high. This powder is the spirit of the new socio-political formation superior to the slave-owning system of ancient Greece. History may hibernate for centuries, accumulating imperceptible qualitative changes. But then quantity develops into quality. The result is an explosion, in the wake of which history shoots forward with the impetus of a freed spring.

Of course, philosophy could teach nothing that the church didn't teach. Its task was simply to demonstrate the truth of Christian doctrines by applying its methods of speculative reasoning. The medieval philosophy, which we today call scholastic, could hardly have seemed dangerous. Like a humble poor relation, it abided by the programme laid out for it—but its very existence already meant the separation of knowledge from faith.

The history of knowledge doesn't stand still. By the 13th-14th centuries many facts unknown to Democritus and Aristotle had accumulated. The first genuine natural sci-

entists began to appear, and the first in this glorious cohort was Roger Bacon.

With a consistency remarkable for the 13th century Bacon advocated the experimental method: "In every science it is essential to follow the best method, i.e., to study each thing in the right order, placing the first at the beginning, the easy before the difficult, the general before the particular, the simple before the complex. The presentation must be conclusive, and this is impossible without experience. There are three sources of knowledge: authority, reasoning and experience. Authority is worth nothing if its assertions cannot be substantiated: authority does not teach, it requires only agreement. In reasoning we commonly distinguish between sophism and proof, verifying conclusions by experience."

Scholasticism knew nothing of the kind. As late as the beginning of the 17th century one clergyman, in response to an offer to see the spots on the sun in a telescope, said: "In vain, my son. I have read through Aristotle twice and found nothing of the kind. There are no spots. They are merely a result of blemishes in your glasses or in your eyes."

Roger Bacon made a tremendous step forward in the methodology of science. Unfortunately, he himself frequently failed to follow his programme. Great thinker that he was, he had no marked influence either on his contemporaries or on future researchers. His methodology had come before its time. It could not take root in the barren soil of scholastic philosophy. But Columbus was already preparing to embark on his voyage to India and Copernicus was beginning to ponder on the rotation of heavenly bodies.

THE FIRST RELATIVITY PRINCIPLE

Copernicus kept his great work secret for more than thirty years. Only in 1530, his stupendous task completed, did he show it to some close friends.

"Though I know that a philosopher's ideas do not depend on the views of the multitude, his primary purpose being the quest for truth, to the extent that God has revealed it to the human intellect, but nevertheless, at the thought that my theory might appear foolish to many I was long undecided as to whether it would not be best to delay making

my work public and, like Pythagoras, limit myself to conveying its essence verbally to my friends."

Copernicus' friends advised him to withhold publishing it for a while. Their reasoning was sound: the Inquisition. Copernicus saw the first copies of his treatise shortly before his death. He did not live to see the indifference with which the academic world at first greeted his theory, nor the persecutions of the church suffered by his followers.

Copernicus was led to revoke the old world picture by purely physical, as well as astronomical, reasoning. "If one holds that the Earth moves," he wrote, "one will, of course, say that this movement is natural, not forced. All that is natural produces an effect opposite to that achieved by force. Things to which a force or impelling action is applied are necessarily destroyed and cannot exist for long, while those created by nature remain in accord with it and are in the best. Ptolemy need not have feared that the earth and earthly bodies would be destroyed by rotation produced by the action of nature, which differs greatly from actions caused by art or industry. Why did he not fear the much swifter motion of the world, for the heavens are much bigger than the earth?"

Copernicus' argumentation, we see, ascends to the faraway prototypes of ancient natural philosophy.

With Aristotle the natural circular motions of the heavenly spheres were contraposed to the forced, rectilinear natural motions in the sublunary sphere. Copernicus replaced this world picture with a system whose natural order is preserved from the first day of creation.

Subsequently this natural order of a system moving "without impelling action" would be developed by Newtonian mechanics into a law establishing the proportionality of force and acceleration in Galilean systems.

Copernicus made ample use of the rich heritage of antiquity. But he also subjected some of the apparently most firmly established truths to a radical re-evaluation, providing new answers to old questions and thereby undermining the ancient world system and breaking down the wall separating terrestrial from celestial mechanics.

Decades would pass and Galileo would see moonscapes in his telescope which he would find analogous to terrestrial landscapes. This would not surprise the great Florentine either, for the earth and heavens obey the same laws. Gali-

leo's discoveries were made possible not only by the magnifying glass, which he was the first to use to look up at the sky. Experiments are blind without clear theoretical premises. That is why Copernicus' theory was so important to Galileo.

It was not enough to spot four little stars next to Jupiter and call them the Medici planets; one also had to realize that they were planetary satellites, moons, thus ditching age-old notions of the uniqueness of the moon and earth. Thanks to Copernicus' theory Galileo already knew that Venus should be more commonly observed as a crescent, and this helped him discover the phases of that planet. The apparent changes in the positions of sunspots provided him with the proof that the sun, like the earth, rotates on its axis at a rate of about one revolution a month. Observing that the Milky Way consists of countless stars, he extended Copernicus' theory beyond the confines of the solar system and showed that the sun was but one of the stars in an infinite cosmos.

In his works Galileo makes the planets revolve about the sun on circular orbits instead of elliptical ones, as had been shown by his great contemporary, Kepler. But this was most likely done to help the layman visualize the Copernican system more graphically.

Galileo, however, was still incapable of thinking in terms of interactions of celestial bodies, and he ascribed the motion of planets to natural properties characterizing the universe since the beginning of time. Hence he denied the relation between the moon and sun and the tides. Here we find in Galileo's conceptions echoes of the Aristotelian system. Even rejected it continued to influence minds! And to this day, in fact, we list Aristotle along with the greatest physicists of all time: Aristotle, Galileo, Newton, Einstein. They were beacons on the crossroads of infinities who illumined the way for human thought through the fathomless depths of time and space.

One of Galileo's main tasks was to prove the correctness of the Copernican system experimentally in terrestrial conditions. First of all, it was necessary to resolve the fundamental problem: does the earth rotate or not? Considering it, Galileo arrived at the famous relativity principle which has, basically, become one of the fundamentals of modern mechanics. To his contemporaries Galileo's relativity prin-

ciple was almost as paradoxical as the special theory of relativity appeared to people at the beginning of this century. In fact, in many ways it presaged the formulation of the basic principles of Einstein's theory.

In his *Message to Ingoli* and *Dialogues* Galileo stages a mental experiment. He offers the reader to imagine a ship. In a room below decks people jump, and juggle with things, fish swim in a tub of water, gnats fly about, smoke ascends to the ceiling, water falls drop by drop into a bottle. When the ship is riding motionless at anchor the gnats fly with the same speed in any direction, the smoke curls straight up, the drops of water fall straight into the bottle. But this picture does not change when the ship moves on a straight course at a uniform velocity and without rolling or pitching, and the people in the room have no way of deciding whether the ship is in fact moving or still riding at anchor.

It is significant that Galileo's ship does not move strictly in a straight line but along an arc on the circumference of the globe. This, incidentally, enabled Galileo to extend his principle to all bodies moving relative to the earth. Contrary to Aristotle and scholasts, Galileo showed that, without observing the stars, it was impossible to detect the rotation of the earth which, incidentally, does not produce the catastrophes predicted by the advocates of a fixed planet. Bodies fall vertically down and projectiles launched at the same speed and angle to the horizon must fall at the same distance whether to the west or to the east.

Today we know that this is true only in the first approximation. In actual fact falling bodies do deflect to the east and even slightly to the south. A rocket launched eastward will fly farther than an identical rocket launched to the west. However in Galileo's time cannons did not shoot far and were so inaccurate that there was no chance of detecting any difference in the flight of a shell shot to the east or west. And a body even when dropped from the height of Pisa's famous leaning tower is deflected by the earth's rotation no more than one millimetre to the east. Even in our time disturbances caused by a body's flight through the air would make it very difficult to detect the deflection.

Only at great velocities comparable with that of light, as for example in the motion of particles in accelerators, and in the movement of bodies in the vicinity of large gravi-

tational masses, as in the case of Mercury which lies close to the sun, does the classical mechanics of Galileo and Newton cease to be accurate and is superceded by the mechanics of Einstein. One should not, of course, regard the imperfect constructions of Galileo, bedevilled by the tremendous difficulties of the first steps of science, as some presage of Einstein's mechanics with inertial motion in a gravity-warped space. Galileo was much too far from this and he measured time with sundials or water clocks. He had not the slightest doubt that light beams were strictly rectilinear, although in our twentieth century it was the telescope again which helped to discover, in complete agreement with the general theory of relativity, their deflection near the sun during an eclipse. Galileo suspected that light does not propagate instantaneously and he even tried to measure its velocity. But with the accuracy of measurement available to him he could only draw the conclusion that light propagates practically instantaneously.

Galileo, the man who discovered the law of inertia and the laws of fall of ponderous bodies, strove to prove that bodies would not be thrown off the surface of the earth because of its rotation even if the force of gravity and the acceleration of falling bodies due to it were quite small. And yet, had Galileo been more thorough in estimating the infinitely small displacements of a body owing to its motion at a tangent to the surface of the earth and falling toward its centre, he would have obtained the velocity at which a body leaves the earth and becomes its satellite.

Galileo made the discovery that the period of oscillations of a pendulum (a chandelier in a cathedral) does not depend on the pendulum's sweep; he did this, incidentally, using his pulse for a watch. He unhesitatingly extended this property of the pendulum to the case when the string is almost parallel to the ground, though this yields a perceptible error. But these examples are in no way detrimental to Galileo's fame.

Science developed a correct understanding of the general case of mechanics of relative motion only many years after Galileo or Newton, and even Lagrange or Euler. Little more than a century has passed since Coriolis calculated the effect of deflecting, or deviating force of the earth's rotation which explains the peculiarities of the motion of bodies on the earth, notably such phenomena as the underwashing

of the right banks of rivers in the northern hemisphere and the formation of cyclones in the atmosphere. In calculating a body's motion the earth can be assumed motionless, but the equations of motion must include, in addition to the force of gravity and the drag of the atmosphere or another medium, the centrifugal force generated by the earth's rotation and the so-called Coriolis force, which always acts perpendicular to the relative velocity of a particle with respect to the earth. This explains the deflection of falling bodies from the vertical.

Difficulties in grasping all the aspects of relative motion remain to this day and occasionally serve as a source of unpardonable errors. As Galileo said, in science much becomes simple and apparent only after long and difficult initial reflection.

This was the case with his investigation of the motion of bodies in terrestrial conditions. For many years the minds of scientists were obfuscated by Aristotle's misconception that the velocity of falling bodies is in proportion to their weight. Galileo refuted Aristotle's theory by logical reasoning applying it to the case of two falling bodies tied together with a string. According to Aristotle, the heavier body must fall faster and the lighter one, slower. But if they are tied together, then obviously, the fall of the heavier body should be retarded by the slower-moving lighter one. On the other hand, the two bodies are joined together, constituting a single body of their combined weight, and as such, according to Aristotle, it should fall faster than each body separately. The contradiction is apparent.

Not satisfied with his reasoning, Galileo went on to stage many experiments with falling bodies, both vertically and along inclined planes. They all bore out the paradoxical, for his time, conclusion that, neglecting the resistance of the air, the rate of fall is the same for all bodies. Galileo found that bodies sliding down an inclined plane with very little friction attain the same velocity, which depends not on the inclination of the plane but solely on the height from which the body ultimately descends from its state of rest. This result of Galileo's is antecedent to the law of conservation of mechanical energy and can easily be generalized for the case of motion of bodies without friction and, in particular, for the pendulum.

Using a water clock, Galileo also showed that the time

needed for a body to descend from the same height is proportional to the length of the plane. Further, he observed that when motion starts from rest consecutively equal distances are passed through in time intervals proportional to the series of odd numbers and the total distance travelled is proportional to the square of the time of descent.

Galileo postulated that the velocity of falling bodies increases in proportion to the time that has passed from the moment the motion began from a state of rest. He drew a graph of velocity as a function of time and, calculating the relevant areas on the diagram, in effect carried out an operation of integration, theoretically defining the laws of changing distances and arriving at what he had already discovered experimentally.

After thus substantiating his new theory of falling bodies, Galileo embarked on a study of the deflection without loss of speed, from vertical fall to an inclined plane. In the manner of the time, Galileo's mathematical reasoning and proofs are in the form of Euclidean proportions. To us the method employed would appear extremely unwieldy and tiresome. As a rule the introduction of special symbols considerably simplifies and improves the mathematical apparatus at all stages of its development. Unfortunately, in Galileo's time the symbolism of algebra, which could have enabled him to obtain some of his results almost without effort, was still in the developing stage. Galileo, however, made extensive use of geometrical methods in solving his problems of motion. He was very adept at this and many of his constructions are extremely beautiful. Even for us solution of these problems by analytical methods presents difficulties.

Galileo was one of the first to grasp the logic of infinity. His example of the paradox of infinity is quite appropriate to the present-day theory of countable sets. It is apparent that the number of squares of whole numbers must be less than the total number of whole numbers. On the other hand, all the squares can be numbered and, hence, there are as many of them as there are whole numbers. The thing is, Galileo points out, that we cannot apply to infinity such words as "more", "less" or "equal" in their conventional sense.

THE DARK AGES TO THE TWENTIETH CENTURY— A DIGRESSION

The closer our narrative approaches modern times, the more difficult is it to preserve its chronological order. This is understandable. Science ceases to be a domain of individual geniuses and becomes a field of collective creative endeavour. In ancient times decades and even centuries could pass between the enunciation of two fundamental physical theories; in later periods one investigator followed another in a matter of years; in our time hundreds of physicists in many countries are engaged in the same problems. In addition, the problems themselves have become more complex and ramified. To present a more or less comprehensive exposition of only the main ones we must not only delve into the past but also look into the future. In the circumstances much has to be omitted completely.

It is with regret that we must refrain from telling the story of the great Florentine, Leonardo da Vinci, or of the celebrated astronomer Tycho Brahe, who toppled the Ptolemaic system. On the other hand, we shall speak of one Bernardino Telesio (1508-1588), a man who has in no way influenced modern natural science or has any significant discoveries to his credit.

Telesio is noted for having founded a society of natural scientists, the Cosenza, or Telesian, Academy, to attack Aristotelian natural philosophy. In his writings he postulated the existence of a single primary matter and two primary forms or principles, heat and cold. All bodies owe their existence to the action of the two principles on the primary matter. Heat is concentrated mainly in the heavens, cold, in the core of the earth; a result of this has been the appearance of living creatures on the surface of the globe. The heavenly heat is irregularly distributed, and steller regions are warmer than those devoid of stars. Owing to these irregularities the initially uniform motions of the planets became irregular.

No, we have mentioned Telesio's theories not for any bearing they may have on the subject-matter of this book. But Telesio presents an interesting example of a sudden reversal to methods and principles that had apparently been rejected for good. Contrary to the whole course of development of the natural sciences, contrary to facts—

suddenly someone attempts to revert to the lost sources. It is not without interest to examine the psychological aspects of such an attempt. One could, of course, compare Telesio's theories with Greek natural philosophy and demonstrate how much they lose in such a comparison. This is not at all difficult. Take, for example, the theory of colours. Telesio explains the origin of colours in terms of his two principles: heat engenders white, cold—black. The other colours are produced, by the mixing of these two basic colours, just as suggested by Telesio's arch-enemy, Aristotle. Clearly, so much time and place need not have been wasted for such a comparison. Who can be genuinely interested in Tolesio today?

Our aim is a different one. Our interest is not so much in Telesio as in events of the more recent past. You may have seen the film *Ordinary Fascism* which offers a philosophical investigation of the basic aspects of life in the Third Reich. Except one: the film says hardly anything about Nazi science. But besides Nazi racial theories there also existed Nazi physics. In the time of Einstein, Rutherford and Bohr there existed a world system more in line with the occult doctrines of the Middle Ages. It was this we had in mind in setting forth the principles of Telesio. This world system was known as "Herbiger's cosmology", and it was an official doctrine of the Third Reich. The description of this "cosmology" has been taken from a book by Powells and Bergier called *The Dawn of the Magi.*

One summer morning scientists throughout Germany and Austria received a letter:

"The choice must be made now, whether to be with or against us. While Hitler purges politics Hans Herbiger will sweep away the false sciences. The doctrine of eternal ice is a portent of the German people's renascence. Beware! Join our ranks before it is too late!"

The man who issued this challenge to the scientific community was sixty-five years old. His theory became publicly known as WEL (*Welteislehre*: "world ice teaching"). His explanation of the universe ran contrary to generally accepted astronomical and mathematical data, but it upheld ancient myths. Nevertheless, Herbiger regarded himself as a scholar, and his science was to choose other ways and other methodologies.

"Objective science is a harmful invention, it is a totem

of decay." Like Hitler, he considered that "the main problem of scientific activity is to know who wants to know". Only a prophet can aspire to science, for he is enlightened and thereby elevated to a higher level of conscience. Hans Herbiger tolerated no doubts, not the slightest hint of contradiction. He was fired by holy wrath: "You put faith in equations, not me!" he raved. "How much time do you have to waste before you see that mathematics is a fallacy with no value whatsoever?"

Herbiger cleared his way with shouts and blows. He was not alone; he was merely the first. Another Nazi cosmologist declared that we are living on the inner surface of a hollow sphere. Hitler and Himmler had an astrologer, though they did not make his prophesies public. The astrologer's name was Fuehrer, and after their advent to power they declared him "plenipotentiary of mathematics, astronomy and physics".

In intellectual circles Hans Herbiger was busy setting up a system of political agitators. He had substantial monetary funds and he acted like the leader of a political party, launching a movement with an information service, recruiting offices, propagandists and thugs recruited among the Hitlerjugend. His men plastered posters all over the place, inundated newspapers with advertisements, distributed pamphlets and held meetings. His adherents broke up conferences of astronomers with cries of "Down with orthodox scientists! Follow Herbiger!" Professors were hounded in the streets. The heads of scientific institutes received postcards: "When we take over you and the likes of you will go begging in the streets." Businessmen and industrialists made new employees sign statements such as "I pledge to believe the *Welteislehre*." Herbiger wrote to leading engineers: "Either you learn to believe me or you will be regarded as enemies."

In the course of a few years the movement published three big volumes setting forth the theory, forty popular books and hundreds of pamphlets. It printed a monthly magazine, *Key of World Events*, in a large circulation. It recruited tens of thousands of adherents. It played a significant part in the history of ideas and simply in history.

Scientists at first protested and printed letters and articles revealing the absurdity of Herbiger's system. They became alarmed when WEL acquired the dimensions of a

broad popular movement. After Hitler's advent to power resistance to the theory began to decrease, though universities continued to teach the orthodox astronomy. Eminent engineers and scientists embraced the world ice doctrine. Among them was Lenard, who claimed priority in the discovery of X-rays, and the physicists Obert and Stark, whose researches in spectroscopy were widely known. Hitler gave Herbiger his full support and confidence.

"Our Nordic ancestors gained their strength in snow and ice," wrote one WEL leaflet. "That is why belief in the world ice is the natural heritage of the Nordic man. One Austrian, Hitler, threw out the Jewish politicians, another Austrian, Herbiger, will throw out Jewish scientists. The Fuehrer has demonstrated by his own life that a diletante stands higher than a professional. Another diletante is needed to give us a complete understanding of the universe."

Herbiger's doctrine derived its strength from a unified perception of history and the evolution of the cosmos. It explained the origin of the solar system, the origin of the earth, of life and spirit. It described the world's past and outlined its future changes. It answered the three main questions: "Who are we? Where have we come from? Whither are we going?"

The fundamental concept is that of endless strife between ice and fire, between forces of repulsion and attraction in infinite space. This struggle, this continuously changing tension between opposing principles, the eternal war in the sky which is a law of the planets, also governs the earth and living matter, thus determining human history. Herbiger claims to offer a description of the earth's remotest past and most distant future. He introduces fantastic notions into the evolution of living creatures. He overthrows all our conventional notions of the history of civilizations and the origin and evolution of man and society. He describes a series of rises and falls. Thousands and millions of years before us there existed godlike people, giants and fabulous civilizations. We may yet become like our ancestors after passing through the cataclysms and mutations of a history which develops in cycles both on earth and in the cosmos. For the laws of the heavens are the same as the laws of the earth, and the world takes part in a single motion, for it is a living organism in which everything is reflected in everything. The fates of people are linked with the fates

of stars, everything that takes place in the cosmos takes place on earth, and vice versa.

It will be observed that the doctrine of cycles and quasimagic relations between man and the world is akin to the most ancient traditional beliefs. It reintroduces ancient prophesies, myths and legends, occult astral teachings and ancient Indian mysticism, astrology and demonology.

This doctrine contradicts all the findings of science. But, Hitler declared, "There is a Nordic National-Socialist science which stands opposed to Jewish liberal science." In a letter to Willi Lei Herbiger wrote how, as a young engineer, he had "once watched a stream of molten metal fall on damp, snow-covered ground: after a time the earth exploded with great force." And that's all; out of this sprouts Herbiger's doctrine.

There was once a huge hot body millions of times bigger than the sun. It collided with a giant planet that had formed through the accretion of cosmic ice. This mass of ice penetrated deep inside the super-sun. For hundreds of thousands of years nothing happened, then the water vapour exploded everything.

Some fragments were hurled so far by the blast that they vanished in the cold space. Others fell back on the central body.

But some of the fragments were hurled into a median zone: these are the planets of our system. There were thirty of them, all of them blocks of ice. The moon, Jupiter and Saturn are made up of ice, the canals of Mars are ice crevasses. Only the earth has not been completely engulfed by cold and on it the struggle between ice and fire goes on.

At the time of the explosion a huge ring of ice lay at a distance three times the distance to Neptune, and it remains there to this day. Official astronomers persist in calling it the Milky Way because several stars resembling our sun can be seen through it. But the photographs of separate stars are no more than a mystification.

The sunspots, which change their shape and position every eleven years, remain unexplained from the viewpoint of the orthodox scientists. They are caused by ice fragments breaking off Jupiter, which completes its circuit around the sun every eleven years.

The planets of our system in the median zone of the explosion are subject to two forces:

(1) the initial force of the explosion, which repels them;

(2) gravity, which attracts them to the largest mass in their vicinity.

These two forces are unequal. The force of the blast is steadily decreasing because space is not empty: it consists of matter, of a mixture of hydrogen and water vapour. In addition, water, which extends as far as the sun, fills space with crystals of ice. Thus the initial force is continuously decreasing. The gravitational force, on the other hand, is constant, and for this reason every planet comes closer to its neighbour. In the process it revolves around it in a steadily decreasing spiral. Thus, sooner or later every planet will fall on its closest neighbour and eventually the whole system will coalesce into a block of ice which will fall on the sun. An explosion will take place again, and it will all start over again.

Ice and fire, repulsion and attraction are eternally struggling in the universe. This struggle determines the life, death and eternal resurrection of the universe.

In 1952 the West German writer Elmar Brugg published a book on Herbiger in which he writes:

"No doctrine purporting to present a world picture has employed the principle of antithesis, of conflict between the two opposing forces which for millennia have been nurturing the human spirit. It is to Herbiger's everlasting credit that he resuscitated the intuitive knowledge of our forebears about the eternal conflict of fire and ice sung in the *Edda*. He expounded this conflict to our contemporaries. He scientifically substantiated a stupendous image of the world based on the dualism of matter and force: repulsion, which scatters, and attraction, which gathers."

Thus, the moon will eventually fall on the earth. For several tens of thousands of years the distances between planets appear to be unchanging, but we shall yet see that the spiral narrows. Over the ages the moon will come closer and its gravitational effect on the earth will increase. Then the waters of the oceans will rise and an eternal tide will cover the land, flood the tropics and engulf the highest mountains. Living creatures will gradually lose weight and grow larger. Cosmic rays will get stronger and their effects on genes and chromosomes will cause mutations. New races of animals, plants and giant people will appear.

When it comes sufficiently close the great speed of rota-

tion will tear the moon asunder and it will become a huge ring of rocks, ice, water and gas, which will spin faster and faster until it finally collapses onto the earth. This will be the Fall presaged by the Apocalypse. If men survive it, the strongest, the fittest, the select are destined to witness weird and terrible sights. And the end of the world may be at hand.

After thousands of years without satellites the earth will witness a remarkable succession of old and new races, new civilizations of giants and fantastic cataclisms. Eventually, Mars, which is smaller than our planet, will draw nearer until it reaches the orbit of the earth. But it is too big to become a satellite and will graze the earth and, attracted by the sun, will fall on it and be consumed in its fire. Our atmosphere will be swept away by Mars and scattered in space. The oceans will boil up on the surface and wash everything away and the earth's crust will burst. Our dead planet will collide with icy planetoids and become a huge sphere of ice which will also fall on the sun. Following this collision there will be a great silence, a great immobility while for millions of years water vapour will gather inside the fiery mass. Then a new explosion of the brute forces of the cosmos will take place.

Such is the fate of our solar system as seen by an Austrian engineer whom Nazi officialdom hailed as the Copernicus of the 20th century.

This mad, blustering gibberish calls for no comment. But it should not be forgotten.

In mentioning Telesio's theory we had no intention of presenting it as a forerunner of Herbiger's "cosmology". More likely than not, Herbiger had never even heard of Telesio. Yet the similarities are too striking to be overlooked. It is as though the two theories are not separated by centuries. Both postulate the opposing principles of heat and cold and evince the same maniacal indifference to the values accumulated by mankind. But then, militant ignorance combined with fanaticism has always taken essentially similar forms.

I have met quite a few foreign scientists. Some of them —likeable people and, of course, highly knowledgeable — went out of their way to emphasize that they were not interested in politics. One would like to ask them what Herbiger's "theory" represents. Is this politics or not? Why is

it that every now and then books exaulting this Nazi "scientist" appear in West Germany?

But it's high time we got back to our narrative.

HAIL, SCEPTIC!

The 16th century, as we have seen, had completely mastered the ancient science. All that had not perished irrevocably was retrieved and made available through numerous translations and commentaries. This, perhaps, is one of the distinguishing features of the age. Natural philosophy and mathematical physics finally parted ways, though physics as such had not yet scored any major signal successes despite the appearance of Copernicus' revolutionary theory.

It was only the 17th century which boldly approached the threshold of the new science. Having availed itself of the experimental method, it was ready for an unprecedented leap forward.

Thus modern or, more exactly, classical physics begins with Galileo.

From here our narrative ceases being consecutive, for it is impossible to set forth the history of atomism, cosmogony and spatiotemporal concepts at the same time. The original source now forks into three separate streams connected with countless channels and branches.

Great contributions to the advance of natural science were made by Francis Bacon and René Descartes. Bacon showed convincingly that contemporary theories neglected experience. Man should become master of nature, he proclaimed. But nature could not be understood without experience, the most valuable source of knowledge. A philosopher should be neither like an empiricist ant nor like a rationalist spider spinning a philosophical web out of no more than his own intellect. In Bacon's view the philosopher should be like a bee which collects its tribute in the fields and meadows to make it later into precious honey.

René Descartes considered the intellect, ably directed toward the investigation of experimental data, to be the key to true knowledge. Experience, experience, and once again experience. This sounded like an exorcism of the foreboding shadows of the Middle Ages. Science was preparing to rise to a new qualitative level and experience was essential.

In Descartes' Nature the spiritual is independent of the material principle; it is pervaded with matter, the basic property of which is continuous extension. The ancient atomists were wrong, and there is no such thing as the void. The material world is in eternal motion according to the laws of mechanics. Hence all natural processes can be reduced to spatial displacement of matter.

However, as the necessity of motion does not derive naturally from the extension concept, Descartes, unlike Bacon, postulated the theory of an initial impulse which imparted motion to the infinite continuous extension.

Baruch Spinoza rejected Descartes' dualism. Nature itself is God and, according to him, it requires neither a spiritual essence nor a creator. Nature is eternal substance in infinite space. It is "a cause in itself" (*causa sui*). This is the principal property of substance: to be the cause of existence and attribute of all things. We shall again encounter this property in one of the most interesting hypotheses of the twentieth century: Heisenberg's nonlinear field theory.

Friedrich Engels saw as the greatest desert of 17th and 18th century philosophy that starting with Spinoza and ending with the great French materialists it persistently attempted to explain the world through itself, leaving the detailed justification of this to future natural science.

As we now know, this was the road which natural science took. The most fundamental concepts of the structure of matter and properties of time and space rest on the principle *natur causa sui*.

The first researcher who turned seriously to the ideas of the Greek atomists was the French materialist philosopher Gassendi. A contemporary of Galileo and Kepler, he attentively followed the gains of the reviving natural science.

In his principal work on the philosophy of Epicurus, Gassendi not only set forth the ancient atomistics but expanded it on the basis of facts accumulated over two thousand years. Like Epicurus, he held that weight, which he defined as an "inner urge for motion", the only source of change in nature, was one of the basic properties of atoms, along with dimension and form. Gassendi was the first to postulate the discrete structure of matter, a problem debated to this day. He also introduced the concept of a molecule as a mechanical agglomeration of several atoms.

In elaborating the teachings of the Greek atomists, Gassendi came to the conclusion that the atomic theory could be used to explain physical phenomena in specific, almost banal terms. He compared a mixture of water and wine with a mixture of two kinds of sand in which the different grains are randomly distributed: the sand grains correspond to the atoms of water and wine in the mixture. From here stems the idea that the aggregate states of matter can also be explained in terms of atomic theory.

These ideas made considerable headway. To the Greeks the atom was no more than an abstract concept which defined the limits of our knowledge of the world as a whole. Now it became a means of understanding world processes. This represented a major shift in thought, which in turn contributed to the more rapid development of natural science as a whole.

The Englishman Robert Boyle (1627-1691) was a physicist and chemist in the most modern sense of these words. His motto was "Nothing by hearsay". In his brilliant book, *The Sceptical Chemist*, Boyle attacked alchemists and their methods, showing that all the achievements of alchemy were no more than fortuitous gains. Alchemists, in fact, knew nothing, were incapable of knowing anything about the nature of things.

Boyle's greatest contributions are in theory of gases. He enunciated the law that the product of the pressure and volume of a gas is constant for any given temperature—a must for generations of schoolchildren. He was the first to formulate the concept of a chemical element as a substance that cannot be broken down further by any means. The ancient Greek concept of elements was associated with the fundamental phenomena of nature: rest, motion, earth, fire, etc. With Boyle the concept is purely materialistic and linked only with chemical processes. His studies of chemical transformations of substances led him to investigate the problem: What are the bricks out of which it is possible to construct the infinite diversity of homogeneous substances?—a question that has not been completely answered to this day. Boyle sought to get to the root of things, he wished to discover the basic elements which could not be transmuted one into the other and of which the whole of the surrounding world was in some way made up. We see that the very formulation of the question is rooted in the fundamen-

tal problem of alchemy. Alchemy, in the wake of the vague ideas of ancient philosophy that nurtured it, proceeded from the postulate that all substances could be reduced to a single primary substance. Yet all the alchemists' attempts to effect such a transmutation failed. Evidently, it could not be achieved by chemical methods. The apparent conclusion was that matter is not uniform on the chemical level and there exist substances which are not reciprocally transmutable by any chemical processes.

Since Boyle's time it has been known that there exist a number of, chemically speaking, basic substances as opposed to thousands of homogeneous chemical compounds, as we call them today. The number of basic substances is much smaller than that of compounds, and Boyle understood this quite well: "It is necessary to determine the basic substances into which matter can be decomposed by chemical means, and what these basic substances are." As we see, Boyle's chemical elements had nothing in common with the elements of Democritus—earth, water, air, fire.

Boyle called his particles of matter corpuscles, not atoms like Democritus. Actually, the modern understanding of the concept "atom" differs from that of Democritus. His atoms are rather what we now call elementary particles. This, of course, is a question not of terminology but of essence. Boyle distinguished corpuscles of the first and second order. The primary corpuscles are the smallest and imperceptible. They possess no qualities but vary in shape and they join together by means of tiny hooks and burrs; the secondary corpuscles are the fundamental components of all bodies. Hence, according to Boyle, things possess primary and secondary qualities.

Matter possesses only primary, purely mechanical properties: shape, dimension, motion, rest, etc. As distinct from these, the secondary properties are subjective. A pin, Boyle pointed out, doesn't possess the property of pain, which you feel when it pricks you. But it does possess sharp form, and pain is a result of the action of that form on our senses. Such qualities as colour, smell, sound are also subjective. They do not exist in nature and appear only when the primary qualities act upon our senses. As we see, Boyle's subjective and purely mechanistic views contained a germ of truth. Modern theories of smell and taste have established the connections between our senses and the structures of

various molecules. But this, of course, the author of *The Sceptical Chemist* could not know. His mechanistic theories served as the basis for Locke's theory of the "primary" and "secondary" qualities of matter.

Where Boyle's ideas stemmed from experimental findings he was far in advance of his age. As Engels said, "It was Boyle who made chemistry a science." From the inverse dependence between a gas's volume and pressure Boyle drew the conclusion that, as the number of corpuscles of gas in a closed volume does not change when the pressure increases, the distance between them decreases. In another remarkable manifestation of scientific insight Boyle postulated that the different states of matter depend on its density and the bonds between corpuscles.

In tracing the development of atomistics we inevitably arrive at the mechanics of Newton. We shall refer to him repeatedly. Whether we take gravitation, the structure of matter, mass or light, in all of these fields Newton has left an indelible trace. It is not for nothing that the inscription chiselled on his monument at Cambridge states: "In intellect he surpassed the human race."

Classical physics is fundamentally Newtonian physics. He discovered the law of universal gravitation and the three fundamental laws of mechanics, enunciated theories of the motions of heavenly bodies and of colours.

Newton did not write anything specifically on atomistics, but from his *Mathematical Principles of Natural Philosophy* and his *Opticks* it is apparent that he had no doubts about the atomic structure of matter.

In the introduction to the *Principia* Newton defines the ultimate purpose of physics as to derive from the principles of mechanics all the other phenomena of nature. In carrying out his stupendous programme he proceeds from the atomic structure of matter. "Experience shows that many bodies are hard. But the hardness of the whole derives from the hardness of its components, hence we justly conclude that the indivisible particles are hard not only in bodies which appear hard to the senses but in all other bodies as well." But Newton's mechanism was closer to ancient atomistics than to modern notions, and, for example, it never occurred to him that at some level in the fragmentation of matter concepts like "hardness" could become meaningless. But then, the novelty of Newton's conceptions

of the structure of matter lies not in this postulating of indivisible particles. His outstanding contribution to the fundamentals of modern physics, a contribution which will most probably never be revised, is the concept of mass. All material bodies possess mass, and the smallest particles of any substance are identical. Following Boyle, Newton states that differences in the properties of different bodies are due to differences in the distances between the particles constituting them. But Newton's particles have nothing in common with Boyle's corpuscles. He provides them with neither hooks nor burrs. His material particles are endowed with forces of attraction and repulsion inherent in all observable bodies of the universe.

This is more than a new leap in the development of natural science. Newton's teaching of mass and force spelled the end of metaphysics in general, and in the strictest sense of the word it is Newton who must be regarded as the "father of physics", for he elaborated the scientific fundamentals of the universe which replaced the fantastic myths and speculative hypotheses concerning the world structure.

THE GREAT LAW AND THE END OF NATURAL PHILOSOPHY

The atomistics of Boyle and Newton on the whole satisfied the physicists; the chemists, however, had some valid complaints. Mechanical atomistics could not explain chemical interactions, thermal processes and other phenomena continually observed by chemists.

We shall see later on that when science appears to be heading into a dead end it is in fact preparing for a new leap. Either a phenomenon will receive an entirely new explanation or some ad hoc postulate will be introduced to take care of the observed properties and resolve the contradictions of theory.

Such an ad hoc component was suggested by the German physician Ernst Stahl to resolve the contradictions of chemical atomistics. He postulated the existence of an imponderable, colourless, odourless substance—the nonmaterial principle of fire, which he called phlogiston, and which joined Boyle's corpuscles together and effected all chemical transformations. It provided a remarkably simple explanation of combustion. Flame, smoke, char, ash are but diffe-

rent forms in the transfer of phlogiston from one substance to another.

The phlogiston theory delighted its contemporaries, who accepted it at once and unconditionally. No one questioned the existence of phlogiston, and when the first convincing facts challenging the theory began to appear, everything was done to salvage it. To explain many observable phenomena it was even necessary to give phlogiston antigravitational properties, though this clearly contradicted one of the basic premises, for originally phlogiston had been held to be imponderable.

Experience gradually undermined the theory. The first to refute it was Mikhail Lomonosov. Unfortunately, his works remained for long unknown to world science. Suffice it to say that in the histories of physics by Heller (1889) and Rosenberger (1882—1890) no mention of him is made at all, while one French historian devotes a few lines which are highly significant:

"Among the Russian chemists who have become famous we should mention Mikhail Lomonosov, not to be confused with the poet of the same name."*

But why speak of the West when in Russia itself Lomonosov's works in physics and chemistry had remained unknown or forgotten until the fairly recent past. It is not only the Encyclopaedia Britannica or Larousse which made no mention of Lomonosov's researches in physics and chemistry: even the famous prerevolutionary encyclopaedias of Brockhous-Efron and Granat said nothing of him.

Lomonosov's works cover a variety of physical domains with great thoroughness. He studied the states of matter, elaborated temperature measurements and expanded on Franklin's works on electricity.

The accuracy with which Lomonosov measured the coefficient of expansion of a number of gases is truly remarkable, his error not exceeding three per cent as compared with contemporary data. This means that for many purposes we could employ data obtained more than two hundred years ago!

Lomonosov used a refracting telescope to observe the transit of Venus across the Sun. He noticed that the edge

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* In fact, Mikhail Lomonosov the chemist *was* Mikhail Lomonosov the poet.—*Tr.*

of the planet appeared washed-out and deformed on approaching the limb of the sun, from which he correctly inferred that Venus has an atmosphere. Yet this discovery remained unknown for many years and some astronomical books still claim that the Venusian atmosphere was discovered only in 1882.

We shall not dwell here on the complex reasons for the "tragic fate of Lomonosov's scientific works, which left no apparent trace in physics or chemistry", to use the words of Academician P. I. Valden. This is discussed at length by P. L. Kapitsa in his book, *Lomonosov, Franklin, Rutherford, Langevin*.

Lomonosov's greatest achievement was his experimental proof of the law of conservation of matter. In 1756 he staged a classical experiment in which he heated leaden lamina in a sealed vessel and showed that, though the lead became oxydized in the process, the weight of the vessel had not changed. The experiment is similar to the famous one carried out independently of the Russian scientist by Lavoisier—17 years after him.

"It is difficult," writes P. L. Kapitsa, "to name a contemporary of Lomonosov who could compare with him in the scope of his researches or the diversity of his interests and knowledge. Lomonosov's theoretical views in the scientific fields in which he carried out his experimental work—heat, the states of matter, chemistry—are remarkable for the degree to which they coincide with the lines along which these fields developed since his time and are continuing to develop to this day."

Lomonosov had a clear idea of the kinetic nature of heat, associating heating with an increase in the translational and rotational motions of corpuscles—which made the phlogiston postulate quite superfluous. Consistently and logically developing his ideas, Lomonosov arrived at the notion of absolute zero. In section 26 of his *Reflections on Heat and Cold*, he writes of "the greatest possible degree of cold caused by the complete rest of particles, the termination of any motion by them". From the viewpoint of classical thermodynamics this conception remains valid to this day.

Like Newton, Lomonosov proceeded from the notion of the qualitative unity of the macro- and microworld. His "insensible particles" possess spatial extension and shape

like any other body, but they are impermeable and cannot be divided into smaller portions. In this sense his relativistic conceptions did not go beyond the conventional ideas of natural philosophy. At the same time, Lomonosov's postulate was a forerunner of the concept of atomic weight, for his "insensible particles" possessed different mass. The property of motion is inherent in them: "Corpuscles in creatures animate and inanimate are in motion, they are in motion in plants living and dead, even in minerals or inorganic bodies—hence, in everything." And hence, the cause of all qualitative changes in physics and chemistry is motion.

Lomonosov's atomistics provided the basis for his teaching on molecules. "An element (atom, according to Lomonosov) is the part of a body which does not contain any other smaller or differing bodies. A corpuscle (molecule) is a collection of elements constituting one small mass."

Basically, this definition does not contradict present-day notions of atoms and molecules.

The works of Galileo, Leibnitz, Newton and Descartes provided philosophers with a wealth of material for generalizations. The advance of physics required a satisfactory definition of matter and its inherent properties. Till then matter had been but a term denoting something unspecified; now it had to be provided with a clearcut explication. Already the 17th-century English materialist, John Toland, in a polemic with Descartes and Spinoza, showed that to reduce matter to extension or define motion only as a modus of matter fails to reveal either the true source of motion or the remarkable diversity of forms of matter. He suggested that motion be treated as a primary inherent property of matter inseparable from it. Matter is of necessity as active as it is extended, Toland wrote, displaying remarkable foresight with respect to the dialectical unity of matter and motion. However, he did not go as far as the idea of evolution and held that nothing absolutely new can ever appear in nature.

Still, in many ways Toland's views predetermined the evolution of the concepts of space, time and motion. Thus, the 18th-century French materialists also held that motion is an inherent property of matter serving as the only source of motion. Wrote Holbach, "The concept of nature necessarily includes the idea of movement. But, people will ask, whence does nature derive movement? From itself, we say,

for it represents a great entity outside of which nothing can exist. Movement, we say, is a mode of existence deriving of necessity from the essence of matter; and matter moves by virtue of its own energy, its motion being caused by forces inherent in it."

Be it remembered that these words were written in the 18th century when there were no clearcut definitions of beautiful formulas behind the words "matter" and "energy". Today, of course, we know that it is wrong to call matter only those forms of its existence which possess mass. Energy is also matter, and in Einstein's celebrated formula, known in our time to so many laymen, mass and energy are linked in a very direct and simple relationship. Furthermore, the concept of a quantum presumes a primal unity of these forms of existence of matter. The French materialists knew none of all this. Their greatest accomplishment was their total rejection of the primacy of the spirit over matter. They did their best to make their speculative premises agree with the data of natural science. As Diderot wrote, "In the view of some philosophers, a body is not of itself endowed with either action or force. This is a terrible misconception that directly contradicts all physics and chemistry."

To be sure, 18th-century physics or chemistry hardly provided the philosopher with a sufficient number of empirical factors in support of this claim. It could, however, be suggested by the specific features of the natural sciences, the invincible logic of their development.

The French materialists following Toland, however, treated motion as simple displacement in space. Diderot, to be sure, went somewhat farther than Holbach, who regarded motion as the force that causes a body to change, or strive to change, its position. Diderot speaks, in addition to external, spatial motion, of the internal, hidden, molecular tension of a body. "A force acting on a molecule may be exhausted," he wrote. "The force inherent in the molecule cannot be exhausted; it is immutable and eternal." From this Diderot derives the relativistic notion of the absolute nature of motion and relative nature of rest. From the purely philosophical standpoint the launching pad for the relativity theory was ready. It was now time for physics to have its say.

After Lavoisier no self-respecting natural scientist pursued his studies without the help of scales. Quantitative determination of the composition of a substance provided the information required for the experimental verification of atomism. Natural philosophy was done away with once and for all.

In 1797, the German chemist Richter discovered that chemical elements enter chemical compounds in definite weight ratios. Thus, in the reaction of hydrogen with oxygen the gases had to be in the ratio 1:8. Only in this case would nothing but water remain in the reaction volume as a result of the chemical transformation.

Ten years later John Dalton elevated this law to the status of a fundamental principle of chemistry, which subsequently linked chemistry with the atomic theory. Dalton offered a more precise formulation of the law and gave it geometric meaning. If hydrogen reacting with oxygen yields water this means that the atoms of the elements oxygen and hydrogen fuse into what we today call a molecule of water. How simple it seems! But at what cost! Dalton was the first to demonstrate that substances enter chemical reactions only in whole ratios, never in fractions. The abstract atom thus began to acquire living flesh, manifesting itself in macroscopic effects that could be registered on a scale.

Dalton introduced the concept of atomic weight which physicists and chemists have been successfully using for more than 150 years in both theory and practice. Atomic weight was later Dmitri Mendeleyev's starting point, from which he launched his search of the periodic law.

The concept of atoms geometrically joining into molecules, enunciated in 1803 by Dalton, swiftly evolved into a streamlined scientific doctrine. Already in 1811 Avogadro, by introducing a bold assumption, laid the foundations of atomic theory in chemistry: he postulated that all gases contained in equal volumes in identical conditions have the same number of molecules. This assumption not only proved necessary in determining atomic weights, it became a cornerstone of Dalton's atomic theory. For if one knows the number of atoms and molecules in a given volume of gas one can also establish how the separate molecules are con-

structed. Without such knowledge an error is inevitable, and Dalton in fact made it at first when he set the atomic weight of oxygen at 8. For he had proceeded from the assumption that only one atom of an element is capable of joining with one atom of another, as in the case of hydrogen and chlorine. In other words, Dalton had reckoned without the possibility of several atoms of the same element joining together to form a molecule.

Avogadro's assumption opened up the way for a quantitative determination of the ratios of atomic masses. Although there was no way of determining the absolute number of atoms or molecules in each case this presented no obstacle toward establishing the ratios of molecular masses. Naturally enough, he reflected on the forces binding atoms and molecules; he introduced the concept of valence forces that hold atoms together and hazarded the brilliant guess that they must be of an electrical nature.

Thus, quite a few things were already known about atoms at the beginning of the 19th century. However, as in Democritus' times, scientists could only speculate about their sizes or numbers within a unit of matter. An atom could still be as big as a dust mote dancing in a sunbeam or immeasurably smaller than the tiny living bodies discernible in a microscope. The shapes of atoms and the forces binding them also presented unlimited scope for groundless surmise. Though it was by that time generally accepted that atoms were the smallest particles of matter which could not be further divided by chemical methods, whether such chemical atoms could reciprocally transmute or undergo changes no one knew.

In 1815, Prout declared that atoms are divisible. In support of this contention he pointed out that the atomic weights of elements are whole multiples of the atomic weight of hydrogen. Hence the inevitable conclusion that all elements are constructed of hydrogen, the atoms of which are the "primary and ultimate building bricks" of the universe.

A new stage in atomistics commences with Michael Faraday, who linked atomic theory with electricity. Chemical atomistics was evolving into physical. Faraday found that in electrolysis the amount of material deposited (or liberated) on the electrodes is proportional to the amount of electricity which passes through the solution. He also found that the masses of the substances produced in electro-

lysis by a certain amount of electricity are in proportion as their "equivalent weights", and in the simplest case of one-valence substances, as their atomic weights.

This remarkable conclusion could mean only one thing: electricity, like matter, is atomic in structure. More, it appeared that an atom or molecule of a chemical compound is bound with one or several atoms of electricity, though at the time it was hard to imagine how the binding was effected.

Then, in 1846, Wilhelm Weber postulated that a specific quantity of matter is always associated with a specific quantity of electricity.

The next step in atomic theory is associated with the enunciation of a strict mathematical theory of gases. Clausius, Maxwell and Boltzmann brilliantly substantiated the laws governing the apparently chaotic swarms of gas molecules.

The year 1865 brought atomistics another remarkable achievement, an event which men had been awaiting for centuries: Loschmidt determined the size of the atom in the very first approximation, and from this the number of molecules of gas in a unit volume.

Like Robert Mayer, Loschmidt studied the internal friction in a gas, obtaining a starting point for estimating the size of an atom, which proved to be much less than the motes in a sunbeam to which Democritus had compared them.

Credit for the discovery of free atoms of electricity not associated with atoms of matter goes to Johann Wilhelm Hittorf who studied the cathode effect in rarefied gases, and observed the deflection of cathode rays in a magnetic field. He used the magnitude of this deflection to calculate the ratio of the charge to the mass of the moving particles. As, thanks to Loschmidt, the size of an atom of electricity was approximately known, the proportion found by Hittorf could be used to determine its mass. Today we know that it is about 1/1840th the mass of the lightest atom, the atom of hydrogen. It was Johnstone Stoney who suggested the name "electron" for the free atom of electricity.

Thus, history has led us from Democritus' atom to the discovery of the first elementary particle. We shall now temporarily bid farewell to the beautiful Muse of history, Clio, and approach contemporary notions of the world and the infinities at the crossroads of which we are now standing.

In 1875 one American clergyman declared in a conversation with a college president that everything that could be discovered had been discovered and any further advance of science was well high impossible. The clergyman was not being original: he simply shared the view of most people, including even famous scientists renowned for their major discoveries in what were then called the inductive sciences.

Still, the college president took exception to this view. "In fifty years," he said, "people will be flying like birds."

The clergyman was indignant. "Only angles can fly," he objected heatedly. "To think otherwise is blasphemy!"

This anecdote would not have been worth repeating—it could have happened anywhere—if not for one interesting point. The clergyman's name was Milton Wright, and he had two sons, Orville and Wilbur, who thirty years later flew the first airplane.

This little anecdote is an example of the 19th-century obscurantism which was overthrown by our century.

In 1807, a mechanic by the name of Fulton requested an audience with Napoleon, offering to arm the French navy with ships propelled by steam. "With steam-propelled fighting ships you will be able to destroy England!" the inventor concluded heatedly.

The Emperor heard him out, then said, "Every day I am shown projects one more ridiculous than the other. The other day I had a suggestion to attack the English coast with cavalry mounted on trained dolphins. You are evidently one of these madmen. Go away!"

Eight years later the English battleship Bellerophon taking the vanquished Emperor to St. Helena met the American steamship *Fulton* which sailed briskly past the English vessel.

Following the ship with his eyes, Napoleon said sadly to his companion Bertrand, "I forfeited my crown when I chased that man Fulton from the Tuileries."

We have no way of knowing the course history would have taken if Napoleon had headed Fulton. Perhaps nothing would have changed. This is not to the point. It is interesting to note that the great Emperor may also have been wrong about the dolphins....

However, let us get on with our indictment.

In 1852, Reichenbach described the transmutation of elements by radioactivity and was ridiculed by his learned colleagues, who unanimously rejected his ideas as balderdash.

Count von Zeppelin offered the American southerners his dirigible (the count's sympathies are understandable). He too was laughed at, on more "sound" grounds, to be sure, for had not the French Academy declared that it refused to consider claims for three things: squaring the circle, a tunnel beneath the English Channel, and steerable balloons.

The Channel tunnel has reached the construction stage. Steerable balloons are a thing of the past. In general, it must be said that it was hard going for aeronautical enthusiasts in the 19th century. For example, when Herman Gaswind submitted his blueprints of a heavier-than-air rocket-propelled flying machine to the German war ministry the comment was, "When will this evil little bird be finally thrown out?"

Professor Langley was deprived of his chair at the Smithsonian Institution for suggesting a flying machine with an internal combustion engine.

On the other hand, Professor Simon Newcomb enjoyed the greatest respect in the scientific world and was oft quoted for his mathematical proof of the impossibility of building a flying machine heavier than air.

These examples offer an idea of the spirit of the nineteenth century. Let us see how this spirit affected the development of theoretical physics.

Chemist Marcelin Berthelot proclaimed in 1887: "Henceforth the universe harbours no more secrets." He was echoed by physicist Clausius: "The universe is wound like a clock, once and for all; when the spring runs down everything will end. As for space and time, these are concepts of the human intellect which do not exist in nature."

At the very close of the century Edward Branly, it is said, forbade his children's governess to read them Jules Verne so as not to fuddle their young minds. Branly himself at the time had decided to cease his experiments with sound waves as devoid of any interest.

"Scientists," writes Jacques Bergier, "were preparing to step down from the throne, but first they wished to do away with the 'adventurers': people who reflected, dreamt, were endowed with imagination".

Berthelot launched a resolute attack against the philosophers: "They fence with ghosts in the barren field of abstract logic." How this accusation applies to Albert Einstein! And how the close of the 19th century resembles the post-Aristotelian period, when science was also prepared to grind to a halt and commit suicide. But knowledge is like a quantum of light. Once having appeared it must race through the ages. No halting is possible.

The outlook which categorically rejected everything unknown, and thereby everything new, had a fatal effect on all aspects of science and technology. There is, of course, a degree of chance in the facts that the inventor of melinite landed in jail and the inventor of the internal combustion engine was unjustly hounded. But attempts to show that electrical machines represented a form of perpetuum mobile are an indication of the spirit of the time. On the one hand, there was boundless faith in the power and omnipotence of man, in the absolute knowledgeability and classical simplicity of nature, on the other, there was smugness and rejection of everything currently unknown.

We give credit to the great researchers of the past, but it would be wrong to speak only of triumphs. Mistakes and setbacks can also be instructive, for they teach people to look ahead with a critical eye. Mistakes should be known, if only to escape repeating them.

The greatness of Hertz is in no way diminished in the eyes of future generations by the knowledge that the discoveror of radio waves had written to the Dresden Chamber of Commerce that the investigation of radio waves should be banned as useless.

But let us be objective. The road of the new has always been thorny. In no age was the road of discoveries strewn with flowers. There are countless examples of this. Such is the nature of all that is truly new: it is born in labour. But there is labour and labour. In this respect the 19th century was truly unique. Innovators had to overcome the resistance, not of individual conservative die-hards, but in effect of the whole of official science.

Experts of Napoleon III proved that Gram's machine would never work. Eminent scientists wrinkled their noses when mention was made of the invention of the automobile, the submarine, etc. The electric bulb was shrugged off as "a fraud". And here is an extract from the minutes of the

Academie francaise on the first demonstration of the phonograph: "The machine had hardly uttered a few words when the Permanent Secretary rushed at the swindler demonstrating it, grabbed him firmly by the throat and exclaimed, 'You see gentlemen, from where sounds are coming.' However, to the amazement of those present, the machine continued to talk."

The man of the 19th century stood at the crossroads of infinities surrounded by a wall claimed to represent the ultimate truth. It fenced him off from the future and the past. Many scholars regarded fossil finds with contemptuous distrust, for had not Helmholtz said that the sun's radiation was due to contraction, hence it couldn't be more than several hundred thousand years old? Of what evolution of matter could one speak in the circumstances? Of what past?

The omnipotent ether, which we shall still have occasion to speak of, smothered all new ideas about matter and space. At the end of the 19th century Lord Rayleigh presented a picture of the ether as a mass of revolving, interacting tops.

It is considered that the man among Einstein's predecessors who came closest to the relativity theory was Henri Poincare. Even if this is so, Poincare simply didn't dare make the discovery. His aphorism that if the universe contracted to a millionth of its size the fact would remain undetected by an observer was quoted with relish by scholarly men, for it was quite in the taste of the age. To be sure, one man did object to the celebrated mathematician that, in the event of such a universal metamorphosis, the butchers would be the first to know as all their meat carcasses would be torn off their hooks by their own weight. Poincare, however, remained true to himself and his age: "Common sense is quite sufficient to prove beyond all doubt the impossibility of destroying a city with a pound of metal...."

Well, he didn't live to witness Hiroshima.

Obviously it is impossible to fit such an intangible thing as the spirit of a time into specific chronological boundaries. The spirit of the 19th century didn't vanish in the 20th, and the germ of the present scientific revolution ripened in the 19th.

Here is a minor episode dating back to 1912. When Pro-

fessor Frank was taking over the physics chair at Prague University he was told by the dean.

"All we ask of you is normal behaviour."

"Why," Frank said with surprise. "Is it such a rarity among physicists?"

"Would you say that your predecessor was a normal man?" the dean objected.

Frank's predecessor had been Albert Einstein.

A throwback to the very normal, decorous nineteenth century.

But the boundaries of "normality" were as a straight jacket to science, which required radical ideas and declared war on self-evidence and common sense. As mentioned before, the germs of this conflict ripened in the 19th century, and for that reason we shall now desist from accusing and speak for the defence.

And so, a brief account of the "madmen" who rebelled against the "normality" surrounding them.

REVOLT AGAINST SELF-EVIDENCE

The first in this list is Max Planck. It is perhaps significant that when, on graduating from the university of Munich, Planck informed Professor Jolly of his intention to take up theoretical physics that eminent academician said, "Young man, do you want to bury your future? Theoretical physics is a finished chapter. The differential equations have been formulated, the methods of solution worked out. Only isolated special cases remain to be solved. Is it worth devoting one's life to such a cause?"

Fortunately, talented pupils often act contrary to their teachers' advice. A man brought up on the best traditions of classical physics was harbouring ideas which subsequently blew up those traditions.

"Max Planck has gone down in history as the discoverer of quanta," writes Abram Joffe. "But, although he caused a revolution in physics, he was no revolutionary himself. On the contrary, he strove to stick as close as possible to the percepts of classical physics. He denied the quantum nature of radiant energy itself and wished to reduce everything to a mechanism of light emission concealed in the depths of the atom. Reluctantly he agreed to extend it to acts of absorption. That Planck's theory rests on a new

hypothesis of quanta was shown by Ehrenfest: Planck himself regarded it as a conclusion drawn from classical theory."

Planck made his discovery while investigating the radiation spectra of heated bodies. At the time science was incapable of stating unequivocally why the colour of radiation depended only on temperature and was in no way associated with the properties of the bodies involved. All attempts to provide a mathematical description of energy radiation by a heated body into empty space were unsuccessful. Frequently the equations led to conclusions contradicting all known human experience. This troubled the scientists. Classical thermodynamics and electrodynamics, unfailing till then, were incapable of solving an apparently simple problem.

At first Planck also approached the problem from traditional positions. The initial results looked awesome indeed, for it worked out that the ultraviolet and shorter wavelengths of the spectrum carry energy away into the void with such a speed that the universe must inevitably cool down to absolute zero. The universe was threatened with an "ultraviolet death".

This was in such glaring contradiction with experience that physicists were distraught. Not, of course, by the prospect of "ultraviolet death" but by the sudden chasm that had developed between experience and theory. It was a theoretical dead end.

The way out was shown by Max Planck. As he said many years later in his Nobel Prize acceptance speech, "After several weeks of the most intense work in my life the darkness in which I had been floundering was suddenly lit up by a flash of lightning and unexpected vistas opened up before me."

Describing the exchange of energy between a heated body and surrounding space, Planck postulated that the process is discrete rather than continuous. The introduction of an infinitesimal, indivisible portion of energy into the theory simplified the formulas remarkably; more important, they described exactly the energy distribution in spectra.

They say that for some time after his discovery Planck was in a state of bewildered anxiety. Perhaps he vaguely anticipated the upheavals it was to cause or began to doubt the world harmony. The concept of discrete packets

of energy undermined the very foundations of classical physics, the edifice of which was now liable to start toppling before the very eyes of its disciples. Whatever the reason, Planck was in no hurry to publish his work. He once remarked to some colleagues that either he has failed utterly or made a discovery on a par with Newton's laws.

One day H. Rubens showed Planck his precision measurements of the energy distribution in a black-body spectrum. They tallied remarkably with Planck's formula. This put an end to doubts. A conscientious adherent of classical physics, Planck finally decided to place the first mine—the quantum of energy—under its foundations. True, in the final formula the energy quantum became a quantum of action, that is, the product of energy multiplied by time. This only made matters worse, for if one could venture to accept the notion of energy quanta, the idea of discrete portions of mechanical action seemed simply mad.

Great ideas have their "relaxation time" in which people get used to, and ultimately accept, them. Only then do they begin to produce new shoots. That is why the repercussions of Planck's revolutionary discovery began to be felt only several years later.

In 1905, Einstein enunciated his theory according to which light is not merely emitted or absorbed discontinuously but actually consists of indivisible quanta, particles which travel in vacuum at a velocity of 300,000 kilometres per second. In the twenties these particles were named photons. The existence of photons does not of itself derive from Planck's conceptions of the discrete nature of radiation and absorption. Einstein explained the relationship between the photon hypothesis and Planck's theory in the following way: "Even though beer is always sold in pint bottles, it does not follow that beer consists of indivisible pint portions."

Succinctly said. Phillipp Frank extends the analogy. If we wish to investigate, he says, whether the beer in a barrel actually consists of definite portions or not we can take a number of containers, say ten different bottles of sufficient size. The beer is poured randomly leaving the amount that gets into this or that vessel to chance. Then we measure the amount in each bottle and pour the beer back into the barrel. This at first glance apparently foolish

operation must be repeated a number of times. If the beer does not come in portions the average value of beer poured into each bottle will be the same for all containers. If it consists of indivisible portions there will be variations in the average values. In the extreme case of the whole content of the barrel being one portion it will pour out each time into one container, and the difference between the contents of the containers will be the greatest, the one containing all the beer, the rest empty. If the beer consists of two, three, etc., indivisible portions the variations from the average values will be successively smaller and smaller. According to these variations, i.e., according to the fluctuations, we can judge of the size of the indivisible portions of beer. From beer it is now simpler to go over to electromagnetic radiation.

Like the beer in the barrel, let it fill a closed box, which we can imagine to be divided into a number of cells. Can we divide the energy of radiation into an infinite number of parts or will we ultimately get down to some further indivisible portions? Incidentally, a similar problem is still awaiting its solution with respect to space and time. But now we are concerned only with electromagnetic field. Thus, if electromagnetic radiation is discrete, what is the value of its smallest portion?

These questions can be answered by measuring the variations of energy among the cells from the average value. If the minimal portions of radiation are large, the variations of energy will also be large, and vice versa.

Measurements show that in violet light (high frequencies) the variations of energy are comparatively large. In red light (lower frequencies) they are smaller.

We can therefore say that "the beer" is not only "sold in pint bottles" but actually comprises indivisible "pint portions". In other words, Einstein came to the conclusion that light is not just emitted and absorbed in indivisible particles: in the interim between emissions and absorptions it in fact consists of indivisible particles whose energy is the greater the higher the electromagnetic wave frequency. The corpuscular structure of light is proved by a number of classical experiments, especially convincingly by the photoelectric effect.

This phenomenon, in which light knocks electrons out of their place, was studied in considerable detail in the

19th century by Hertz and Stoletov. Before Einstein it remained unclear why the energy of the knocked out electrons does not depend on the brightness of the incident light and is determined only by its colour, i.e., the frequency. This observation was in complete contradiction with the classical wave theory of light. Another mystery was the red threshold of the photoeffect. Painstaking measurements revealed that for every substance in the solar spectrum there exists a definite frequency barrier. Rays of frequencies below the "barrier value", i.e., those at the red end of the spectrum, do not cause the photoelectric effect. This observation was in utter variance with the basic premises of the wave theory. Classical conceptions suggested rather the reverse: that light of whatever frequency should knock out electrons, any variations being due only to the brightness, the intensity of the light. Brightness and time, these had to be the only factors of the effect. But no matter how long metal plates were irradiated with monochromatic light lying beyond the red threshold no effect was observed.

Only Einstein's conceptions of quanta proved capable of explaining the photoeffect.

A certain energy is required to knock an electron out of a metal plate. This was realized before Einstein, but it took Einstein to show that to each electron corresponds an absorbed light quantum. The two interact face to face, one to one. The energy of an individual photon is determined only by its frequency. The energy of a "violet" quantum is thus, obviously, greater than that of a "red" one. Hence a "violet" quantum is capable of overcoming the forces holding the electron in the metal while the "red" one may perish without leaving a trace. Everything depends on the degree of "redness" or "violetness", and this explains the red barrier. The energy corresponding to the barrier characterizes the lowest portion capable of ejecting an electron from the surface of a solid body.

Why the energy of an ejected electron does not depend on the brightness of the incident light is explained in equally simple terms. An electron's energy is the difference between the initial energy of the quantum that ejected it and the energy spent by the quantum in overcoming the forces holding the electron. The brightness of light, as any school textbook will tell you, is but a measure of the num-

ber of photons falling per second on a unit surface. Quantity here is of no consequence. What matters is quality, the energy of the photons. Every photon impinges on a body independently, and each one wins or perishes alone. If the energy is sufficient an electron is ejected, if not the quantum is absorbed in the body without any apparent consequences. Quanta are incapable of joint action, they cannot attack an electron in groups of two or three. And this explains why neither the brightness of the incident light nor how long it illumines a surface has any bearing on the energy of photoelectrons.

But in spite of the exhaustive explanation of the phenomenon it provided, the photoeffect theory did not appear to Einstein's contemporaries as clear and comparatively simple as it does to us today.

For, besides being unable to explain such phenomena as the rainbow colours in a film of oil spreading on water or the limiting resolution power of optical instruments, so easily described in terms of wave theory, the newborn quantum theory was, in addition, strange and mad. The photoeffect does not depend on the brightness of the light or the distance from its source. This is strange, very strange. In the words of H. A. Kramers, the effect is the same as if a sailor has dived into the sea and the energy of the wave from the splash reaches the other end of the sea and washes another swimming sailor on to the deck of *his* ship.

The existence of electromagnetic waves and the wave nature of light cannot be challenged, that is certain. But nor can the corpuscular nature of light be rejected. It was not Planck but Einstein who ushered the contradictory duality inherent in nature into the realm of science. It is hardly surprising that contemporaries refused to accept this duality as a true picture of the world. To them it was an inexplicable contradiction.

Small wonder that, in their letter recommending Einstein for membership to the Prussian Academy of Science, several leading German physicists, Max Planck among them, wrote:

"He should not be judged too severely for occasionally losing sight of the objective in his logical reasoning, such as in his theory of light quanta. For in even the most exact of the natural sciences one must take risks to achieve anything really new."

Einstein, however, never had the slightest doubt that light truly possesses both wave and corpuscular properties. He boldly faced the paradox that exploded the classical concept of particles incapable of possessing wave properties and of oscillations which simply cannot have any corpuscular characteristics.

Two decades later Louis de Broglie extended Einstein's conception to all elementary particles and formulated the theory of wave mechanics.

THE ETHER. ITS HEYDAY AND DECLINE

The new world picture emerged from the ruins of the old theories. Rejection of the ether concept meant the downfall of the ordered universe with its intricate clockwork hierarchy of cogwheels. However, before speaking of those whose works produced the cracks in the ether that ultimately led to its demise let us dwell for a while on that ideal substance itself.

The ether concept appeared at a time when scientists were seeking to comprehend the nature of light. Its roots lie in the seventeenth century.

The first ether theory of light was enunciated by the Dutch mathematician, astronomer and physicist Christian Huygens. According to it, every body emitting light, whether a candle or the sun, generates waves which propagate in all directions and reach the eyes of the observer. By then it had been established that oscillations in solids and even in the air generate sound. The waves generated by a tolling bell spread like circles in water. On the other hand, if the bell is in vacuum, where there is no medium through which the waves propagate, sound does not occur. The same reasoning, declared Huygens, holds for light. To be sure, he was well aware that the analogy between light and sound was not complete for, unlike sound, light travels easily through vacuum despite the absence of a material medium capable of transmitting its oscillations. It was this that compelled Huygens to fill the vacuum with the hypothetical ether capable of transmitting waves of light.

In Greek "ether" (or "aether") means "air", "sky", "upper spheres". Natural philosophers had employed the ether concept to explain the motions of the planets.

Newton devoted almost four decades to studying the

properties of light. In 1704 he published his famous *Opticks; or a Treatise of the Reflections, Refractions, Inflections, and Colours of Light*, in which he explained many optical phenomena. His explanations remain valid to this day, and they most likely will continue to be so forever.

A convinced atomist, Newton, following the ancient natural philosophers, held that light must be a stream of particles emitted by the light source: Are not light rays very small bodies emitted by glowing substances? The particles are too small to be seen or measured, but they help explain many light phenomena: rectilinear propagation, reflection from planes, refraction at the boundary of two media, absorption.

At the same time—and Newton was the first to realize this—the corpuscular theory did not cover all light phenomena. In the first place, it failed to explain interference. Newton himself introduced the notion of "ether waves" and expressed the view that both theories, corpuscular and wave, were required to explain light phenomena. As we have seen, this idea was brilliantly confirmed, though on another physical basis, by Einstein. This is not accidental, for it was Einstein who built the new world system that followed Newton's.

Newton readily accepted the ether concept, because he regarded as completely absurd the notion of one body acting on another at a distance in vacuum. No researcher, endowed, in his words, with the capability for consistent philosophical reasoning, could embrace such an idea.

The concept of light as a wave process in the ether was upheld by Lomonosov, Euler and, most successfully, Thomas Young, who explained the phenomenon of interference of light.

Whatever its nature, the ether, in the scientists' view, filled all space, pervading all matter, penetrating between atoms. Acceptance of the ether concept did not, of course, preclude arguments concerning its nature. It was likened to a solid of great elasticity, considered tenuous or extremely rarified, or possessing properties that changed as the occasion might warrant, like sealing wax.

The properties of light were in fact such that they could not be explained without introducing a medium capable of transmitting waves over millions of kilometres without dissipating energy. But did the medium really exist?

Was it not but a physical phantom devoid of form or content or even, as Lord Salisbury put it, merely a noun form of the verb "to oscillate"?

And if the ether did exist, was it at rest or in continuous motion? Or perhaps scientists like the English mathematician and physicist Stokes were right when they claimed that the ether was carried by the earth in its rotation around its axis and the sun?

Among the adherents of the stationary ether was the brilliant French scientist Augustin Jean Fresnel.

In a letter to his brother dated 6 June 1814, Fresnel wrote that he was "greatly tempted to believe in the oscillations of a certain fluid for the transmission of light and heat". This became the point of departure for his work in the sphere of the world ether. Together with Arago, Fresnel undertook to observe the interference of rays in mutually perpendicular planes. The result was negative, and it led him, like Young, who soon heard of the experiment, to postulate the transverse nature of light waves. In transverse waves, it will be remembered, the oscillations are directed at right angles to the direction of propagation. That is how waves spread in water and how a wave runs along a string when one of its ends is jerked sharply. The transverse wave hypothesis was so revolutionary and required such strange qualities to be ascribed to the ether (low density combined with hardness, elasticity and noncompressibility) that the authors themselves introduced it with extreme caution. Young enunciated his ideas with reservations concerning the reality of transverse motions. Fresnel, who as early as 1816 had realized that the experiments "could be easily explained if the oscillations of polarized waves were restricted to the planes of the waves", finally declared acceptance of the view that the oscillations of natural light are transverse only in 1821.

Many people were inclined to support Fresnel's conceptions of the stationary ether because it presented an ideal reference system with respect to which it was possible to envisage absolute as distinct from relative motion. The term "absolute" denoted a quality independent of the position of an observer in the universe. Is the velocity of light absolute? Is it the same for any observer? Is it independent of or, on the contrary, dependent on the motion of the light source?

These questions were eventually answered by the special theory of relativity; it was a problem on a cosmic scale from which sprang conclusions of extreme importance.

Here is what James Clerk Maxwell wrote in his article on the ether in the ninth edition of the Encyclopaedia Britannica: "If one could measure the velocity of light in the time it requires to travel the distance between two points at the surface of the earth and then compare it with the velocity of light in the reverse direction, one could determine the velocity of the ether with respect to those two points."

In a letter published in the magazine *Nature* shortly before his death Maxwell stated his belief that man would hardly be able to answer this question.

Maxwell's prestige was extremely high. A. F. Joffe in his book *Meetings with Physicists* recalls the following fact: "In 1911, when I was working on a kinetic theory of radiant energy based on the photon concept, I met Planck. One can easily understand why I embraced the photon theory, which fulfilled my dream of light without the ether. That, at least, is how it appeared at the time. By considering the equilibrium conditions of photons in a closed vessel I was able to deduce Boltzmann's law and Wien's displacement law. As for Planck's spectral formula, it was valid only on the assumption that the number of identical photons in an elementary statistical cell is infinite.

"Before sending such a, for those times, heretical theory to the press I wanted to show it to the best authority, Planck.... He found my paper interesting but insisted that I refrain from using photons, as being incompatible with Maxwell's electromagnetic theory of light. 'We are indebted to Maxwell for so much that it would be ungrateful to reject his theory. See if you cannot reach the same conclusions without breaking with Maxwell. Everything that can be retained in his theory should be left.'"

Maxwell's theory was certainly extremely beautiful. To this day we use his equations and see in them a brilliant example of scientific precision, completeness and simplicity. The advance of physics has shown that there is no getting along without photons. But Planck was in many respects right. He gave a fine example of truly scientific conservatism, which is at least as important as "mad"

ideas. Before scotching a theory it must be subjected to all-round tests in an attempt to obtain all the necessary conclusions. Otherwise the foundation, the continuity of science disappears, with the danger of it degenerating into barren flights of fancy.

In his theory Maxwell brought electricity and magnetism together in a unified electromagnetic field, which he then extended to visible light and the invisible ultraviolet and infrared portions of the spectrum. To this day specialists are held in awe by the scope of his generalization which embodied in four brief equations all man's knowledge of electricity and magnetism accumulated since Thales' time. It is not just that light was shown to be a wave process capable of propagating through vacuum. Men had already been prepared for this by Fresnel. The most remarkable thing was the electromagnetic waves' ability to exist without any apparent connection with their source, as it were completely on their own. Surrounding space was filled with a very real but intangible substance. Suddenly an aura of strangeness surrounded the abstract mathematical formulas.

Furthermore, here was a direct challenge to tradition. For the first time a fundamental theory was breaking so sharply with mechanical motion. Had Bohr lived in Maxwell's time he would have recognized the theory to be quite mad enough.

But most important, Maxwell's theory contained all the necessary elements we find today in the boldest and most general attempts to describe the world.

Understandably, the mathematical quantities describing field are not easily visualized in terms of conventional images. In their time they were as abstract as the wave function appears today.

It is hardly surprising, therefore, that at the turn of the century—Maxwell's theory was elaborated in 1860-1875—the mathematical abstractions of electromagnetic field were accepted only by physicists of an unorthodox bent. As could be expected, Maxwell's equations described not only known phenomena but also predicted the existence of new and as yet undiscovered ones.

A theory is born of generalization, then it swiftly expands to the limits of its applicability until it reveals phenomena it is no longer capable of explaining. Generalization

of these phenomena yields a new theory, which includes the initial premises of the older one as a special case. Such is the road of advance of natural science. It should be reiterated that science does not strike itself out, as people once thought and some still think today. Science can be likened to a series of nested spheres: the smaller one does not vanish in the larger one: it becomes a part of its flesh and as such continues to exist. Our theories are increasingly illumined by the light of absolute truth. The advance of science serves to outline more clearly the scope of the phenomena they cover. Einstein did not refute Newton. Classical mechanics has entered relativistic mechanics in toto as a special case.

Maxwell's equations were used to predict such unknown phenomena as radio waves and electric induction. They could not, however, refute the existence of the ether. This could be done by the kind of experiment suggested by Maxwell. And yet, the mathematical beauty of his equations was so convincing that some scholars began to see the ether as no more than a special form of vacuum. As for the physicists wholly in the shackles of tradition, they sought to clothe Maxwell's abstractions in conventional mechanical models. Some described the electromagnetic field in terms of a special tension of the ether, others, closing their eyes to the contradictory nature of the ether's postulated qualities, began to regard it as a "weightless substance" which cannot in principle be detected.

Maxwell himself, incidentally, did not fully realize the true wonderfulness of his theory, which drew a sharp boundary between mechanism and the new physics. In this respect he is like many other great transformers of natural science. Planck, as we have seen, regarded Einstein's quantum ideas as unfortunate, if pardonable, radicalism. And Einstein, too, was in spirit more of a classic than is generally realized. This is only natural and easily explainable. History has, to be sure, known scientists who, having said a new word, were prepared to burn their bridges. We shall see further on that the discoveries of radioactivity and particle annihilation gave rise to attempts to reject the conservation laws. But one should always remember the aphorism of Jeři Letz: "When jumping with joy make sure that the ground is not stolen from under your feet."

Maxwell made many attempts to evolve mechanical mo-

dels for his abstractions. Thus, he conceived of hexagonal "molecular vortices" brought into motion by "guide wheels", and he replaced Faraday's force tubes with more easily visualized lines of force, which we still use to teach schoolchildren the fundamentals of electricity and magnetism.

If even Maxwell did not realize at once that the new science he had created was in no need of mechanical props, small wonder that his contemporaries were sceptical and clung to traditional conceptions. The clash with tradition is the first experience of every new idea before it can win over men's minds.

Hendrik Antoon Lorentz has been called the "father of theoretical physics". Once Lorentz, failing to grasp the physical meaning of Maxwell's theory, requested the help of a French researcher who had translated Maxwell's works. The man could only shrug his shoulders: to him the electromagnetic field theory was pure mathematics devoid of any physical content. But gradually in Lorentz's mind the field became as real as the surrounding world. He needed neither Maxwell's little wheels and springs nor Faraday's tubes. He concentrated on the source of the field, the electric charge. This in effect marked the beginning of the electron theory. It was Lorentz who introduced the electron concept into Maxwell's theory, thereby enriching it with the ideas of atomistics. It was only later that Thomson's experiments demonstrated the reality of the electron; the statistics of electrons in metal appeared which was remarkably like the behaviour of molecules in gas; and, finally, the Zeeman effect provided visual proof of the presence of electrons in the atom. But theoretically the existence of electrons was postulated by Lorentz. To him they were as real as electromagnetic fields.

Electrons are scattered in an infinite ocean of electric fields; all things about us, and we ourselves, are made up of combinations of charges. What is field? No more than tensions of the ether around the charges. These tensions pervade all things. They are intangible, but they obey the Maxwell equations. This is the only real manifestation of the ether. In fact, we hardly need the ether when the whole diversity of the world develops from interactions of fields and charges.

"The suggested hypothesis," Lorentz wrote in 1895, "is in a sense a return to the old theory of electricity."

This is not only obvious but quite natural. It is a return to an old theory, but on a qualitatively new basis, and therein lies the dialectics of knowledge. We shall see later on how science returned again to the electricity theory, having rid Lorentz's theory of the ether and its mysterious tensions.

Lorentz's theory made it possible, for example, to compute the refraction indices of transparent substances, which contributed much to the advance of many branches of physical chemistry, and it enriched science in many fields where Maxwell's theory was in need of direct experimental verification. The Zeeman effect also followed directly from the new theory. Lorentz predicted that the action of magnetic field should split atomic spectra. Fizeau's interesting experiment, which for several decades had worried theoreticians, finally received a natural explanation.

In 1851, Fizeau undertook to determine whether a moving stream of water had any effect on the velocity of light. He used the interference phenomenon for his experiment, in which he passed two light beams along parallel pipes through which water was pumped at a high rate, so that in one pipe the light was travelling with the current and in the other against it. He found that light travelled faster with the stream than against it. Lorentz was the first to offer an explanation for the strange paradox.

Maxwell, you will recall, had suggested the idea of an experiment which could be used to detect the ether. I don't know whether Albert Michelson had heard of this or not, but the idea of such an experiment became an ideé fix for him.

It is said that the initial impulse was provided by a remark of Sir Oliver Lodge, a celebrity both in natural science and in spiritualism and sundry other occult sciences. Lodge wrote that in most likelihood a deep-sea fish did not even suspect the existence of the water because it surrounded it equally on all sides. This, he declared, was our situation with respect to the ether.

One could, of course, assume that the stationary ether is a material substance, invisible to us, which pervades all things. But then an observer at the earth's surface should be able to detect an "ether wind", for the earth is hurtling through space at a tremendous speed in its motion around the sun. The ether ocean should slow down light

to some extent: hence a fish swimming in the ocean can detect the motion if it has a sufficiently sensitive instrument. In fact, any swimming creature is well aware, consciously or subconsciously, that it is easier to swim across a moving stream and back than to swim the same distance up or down the stream and back.

Bernard Jeff cites the simple example Michelson used to illustrate the point. The current in a river flows at a speed of 1.2 m per second; the river is 27 metres wide; and there are two men in rowboats; one crosses the river and returns, the other rows 27 metres downstream and also returns to their point of departure. If both men row with the same speed, 1.5 m per second, how long will it take each of them to return to the initial point? The boat crossing the stream moves at right angles to the river current and its velocity can be found from the rule for the composition of velocities: $x=\sqrt{1.5^2-1.2^2}=0.9$ metre per second. Hence it will have crossed the river in $27/0.9=30$ seconds and returned in 60 seconds. The second boat travels downstream at a velocity of 2.7 m/sec and upstream at 0.3 m/sec. Hence it covers the total distance in $27/2.7+27/0.3=100$ seconds. The difference is an appreciable one: 60 and 100.

In the same way, the ether must retard a beam of light directed at right angles to the direction of the earth's motion around the sun less than it does a beam travelling in that direction. If the beam takes the same time to travel in either direction this must evidently mean that there is no ether.

Michelson staged his experiment accordingly, directing two beams of light from one source simultaneously at right angles and then returning them to the initial point. If the ether exists and one beam is retarded this can easily be established by the interference of light: characteristic alternations of dark and bright fringes. The mutual enhancement or cancelling out of light waves travelling out of step was to reveal the existence of the elusive ether. The idea of the experiment was simple.

It was not so simple, however, to carry it out, for light travels with tremendous speed and any retardation by the hypothetical ether would be hardly detectable along the small distances involved. The velocity of light and that of the earth are practically incommensurable: the difference is by a factor of 10,000. Such an experiment required an

instrument of unique sensitivity, for the smallest error could swamp the result. Michelson, though, was undaunted by difficulties.

His experiment followed the same principle as that of Fizeau, with some modifications. Instead of splitting a light beam into two parallel beams, Michelson placed a semitransparent mirror in the way of one light beam which split it into two perpendicular beams; these were reflected back by two mirrors placed at equal distances from the semitransparent one, and joined back into one beam. (Without going into the details, it can be said that this is the principle on which Michelson's interferometer is based.)

Michelson first tested his interferometer at Hermann Helmholtz's Berlin laboratory. Helmholtz thoroughly examined all the factors that might affect the outcome of the experiment. In particular he thought that temperature fluctuations could present a serious problem. "However," Michelson wrote in a letter to Newcomb, "I make bold to disagree. I think the apparatus should be surrounded with melting ice, thus ensuring practically constant temperature."

Michelson was most surprised when the experiment yielded a negative result. The "ether wind" had no effect on the velocity of light. "The stationary ether hypothesis is erroneous," Michelson wrote in 1881 in his paper, *Relative Motion of the Earth and the Luminiferous Ether*. The only conclusion that suggested itself was that the ether was not stationary with respect to the earth, if it existed at all.

Ernst Mach called at once for a rejection of the ether theory. Lord Kelvin, on the other hand, continued to believe in it, while Lodge reformulated his definition of the ether as a continuous substance pervading space the oscillations of which propagate light; this substance can be divided into positive and negative electricity, its vortex motions constitute matter; not discreteness, but continuity accounts for the property of matter to respond to action and reaction.

Lord Kelvin and Lord Rayleigh, meanwhile, approached Michelson with the suggestion to check the effect of a moving medium on the velocity of light. Following Fizeau's example, Michelson took water as this medium and, together with Edward Morley, proceeded to prepare the expe-

riment. The final result of the Michelson-Morley experiment was published in 1887. John Bernal has called it the greatest of all negative results in the history of science.

Although the experiment ruled out the stationary ether, there still remained the possibility that the earth entrains the ether so that its velocity with respect to the surface was nill or very small.

Ten years later Michelson staged an experiment to verify this hypothesis. The result was again negative. But it required Einstein's theory of relativity to finally bury the ether. Meanwhile the Michelson-Morley experiment had done more than led physics into an impasse.

Between 1893 and 1895 two leading theoreticians, independently of one another, attempted to save the ether.

Professor George Fitzgerald of Dublin's Trinity College offered a brilliant and startling explanation of the negative result in the Michelson-Morley experiment. He postulated that all material bodies moving through the ether shrink in the direction of motion. Many ridiculed the notion as the product of an unbalanced mind. None of his contemporaries probably suspected that some of his conclusions would be incorporated in a new physical world system. It is ridiculous to assume that Fitzgerald had simply "invented" a hairbrained theory in an attempt to salvage the ether. After its parting of ways with natural philosophy, physics, as we have seen, ceased engaging in fantasies. Fitzgerald's reasoning was firmly rooted in Maxwell's theory, and the paradoxical properties of high velocities derived directly from the electromagnetic properties of light.

Nevertheless, Fitzgerald's ultrarelativistic hypothesis caused a turmoil in orthodox physics. After all, no one had ever seen a solid ruler shrink, however fast it was made to move. This was contrary to experience and, of course, common sense. True, according to Fitzgerald the contraction could never be detected. For the earth races through the ether and contracts together with all material bodies on it, including the length standard and Michelson's interferometer. This universal contraction thus explains the negative result of the 1887 experiment. Whatever the logic of the case, however, the alarm and madness introduced by Fitzgerald remained. Opponents quoted Josiah Willard Gibbs: "A mathematician can say what he wants, but a physicist should retain at least some fraction of common

sense." Only very few, albeit very serious, theoreticians were genuinely interested in the contraction idea.

Lorentz saw it as providing confirmation of the existence of the ether. Although it challenged common sense, it at the same time put the ether notions from their head back to their feet. The ether became tangible, it could be "felt" with the help of a suitable instrument. For in fact Michelson's zero result represented the first case of the ether action on a material body: the ether displayed itself by making it impossible to detect a body's motion through it! But then, it had been postulated as a certain all-pervading substance with unique properties. It was hardly surprising that the effect of such a substance was universal over all bodies without exception.

Lorentz evolved a streamlined mathematical theory the final equations of which indicated that the contraction alone was not enough to describe moving bodies. It was also necessary to introduce a special time, dependent on the velocity. This was quite incomprehensible, and Lorentz himself regarded the result as no more than an intriguing physical curio. He had no real intention of encroaching on Newton's "absolute time".

Thus Lorentz (like Poincare, incidentally) stopped just short of the relativity theory. He did not, probably could not, make the last step. The Fitzgerald-Lorentz hypothesis was without doubt a very bold one. It brilliantly resolved the contradictions arising from the Michelson-Morley experiment. However—and this must be clearly realized—it was rooted wholely in the laws of classical physics, in the concepts of absolute motion of material particles and possible changes in the velocity of light. It created a turmoil in men's minds and the academic community, but it could not shake the foundations of Newtonian classics.

Lorentz arrived at relativism from traditional bases, which became his barrier. It was a philosophical barrier which the great scientist was unable to overcome. Subsequently he was to say: "Today, setting forth the electromagnetic theory, I declare that an electron moving in a curved path emits energy; tomorrow in this very room I will say that an electron revolving about a nucleus loses no energy. What is truth if one can make such mutually exclusive statements? Can we ever learn the truth, and is there any sense in scientific endeavour?"

This is the reason why Lorentz, in our view, could not detect the precious shoot of relativity theory in the transformation formulas that bear his name. The dialectical contradictions lying at the foundations of phenomena seemed unsolvable to him. He felt this deeply and his latter years were poisoned by scepticism and despair. In a conversation with A. F. Joffe he once confessed, "I have lost confidence that my scientific work ever led to the objective truth and do not know what I lived for; I am only sorry I didn't die five years ago, when everything appeared so clear."

Meanwhile things proceeded from bad to worse. J. J. Thomson, director of the Cavendish Laboratory of experimental physics at Cambridge, discovered the electron and proved the electric nature of matter. Radium, discovered by the Curies, displayed a variety of unusual properties. In particular, physicists found that the electrons spontaneously ejected by it travelled at many thousands of kilometres per second, which seemed totally impossible.

W. Kaufmann, a young German physicist, showed experimentally that the mass of such a superfast electron changes with its velocity: the faster the electron moves the greater its mass.

Mass ceased being constant. As in the postulated Fitzgerald effect, in Kaufmann's experiment the habitual stable world of clearcut stable laws fell apart. Length, mass, time—everything became vague and nebulous.

The world broke apart in the Curie tests
In bursting atomic bombs
Forming great streams of electrons and dust—
*An unfulfilled hecatomb.**

Some people are wont to see something of a prophetic vision of the atomic bomb in these verses of Andrei Bely. Actually the poet had only wanted to present an image of the collapsing world system. The world created by Newton was being torn asunder in the experiments of physicists. It was left to Einstein to finally demolish and, at the same time, salvage that world.

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* Translation by G. Leib.

PART TWO
Building Blocks of the Universe

FIRST ABORIGINE OF THE MICROWORLD

Francis Bacon once said that the most perfect beauty always contains a measure of strangeness. There is a profound meaning in this aphorism. For many years strangeness darkened one of the main domains of physicists: their investigations of the nature of matter.

A theoretician delving into the microworld found himself in an ocean of strangeness, a chaotic congregation of elementary particles. Some of them seemed to be eternal, some decayed gradually, producing new ones, some streaked across the sky like fireballs. To trace the interactions between particles and establish even the simplest laws governing their behaviour seemed a hopeless task.

Lately the picture has cleared somewhat. The very word "strangeness" has become a full-blooded physical term for describing elementary particles, and beauty and order are beginning to appear amidst the intricacies of baffling decay processes and scintillations of vanishing entities.

"When I was entering physics some forty-five years ago," writes Academician I. E. Tamm, "it was undisputed knowledge that there existed two elementary particles, two little bricks of the universe that go into the making of all substances: the electron and the proton."

Actually, that time was a lull before the storm that was brewing in physics. By the turn of the century it had already been established with sufficient credibility that the whole infinite diversity of surrounding nature, animate and inanimate, is a product of various combinations of a relatively small number of elements. The truth of Democritus' great idea had been confirmed once and for all. Molecules, comprising atoms of one or several elements, were regarded as the smallest particles of compound substances

retaining the physical properties of that substance. When a molecule breaks up into its component atoms the properties of the initial substance vanish.

Chemists carried out reactions one more intricate than the other but the best they could achieve was to produce pure chemical elements. Never before had the alchemists' idea of transforming one element into another seemed more heretical. It was a time when few people doubted that atoms represented the primary bricks of the universe. They did not stop to wonder why nature needed so many bricks of different size, from tiny hydrogen to big uranium.

The development of the science of electricity led to the idea of "granulation" and on to J. J. Thomson's discovery of the electron in 1897. This was the first elementary particle. But the action of inertia was so great and the prestige of the indivisible atom so high that the electron was referred to as an "atom of electricity". Soon the electron's mass was determined and found to be vanishingly small: only 9.106×10^{-28} gram, or 1,836 times lighter than the lightest atom, hydrogen. Repeated precision measurements carried out by the American physicist Robert Millikan showed that the electron possesses the smallest known electrical charge, today set at $e = 1.602 \times 10^{-19}$ coulomb.

In his Nobel Prize speech Millikan expressed the paradoxical and strange truth which holds to this day, namely, that in answer to the oft repeated question: What is electricity? the experimenter is compelled to declare his ignorance of the ultimate essence of electricity. This recalls to mind the prophetic words of the theoretician Hermann Weil: "The difference between the two types of electricity is a deeper mystery of nature than the difference between past and present." Albert Einstein managed to show somewhat relative nature of the distinction between past and future; as for electricity, even today we can hardly say more than Millikan about its ultimate essence.

The discovery of the electron did not shake the notion of the indivisibility of the atom. At least, so it seemed to Thomson's contemporaries, although even then the definition of the atom carried within itself the dialectic opposites of indivisible, yet complex.

How did physicists picture the atom at the time? Firstly, a sphere, or rather a spherical cloud, uniformly charged with positive electricity. Embedded in it are electrons,

rather like raisins in a pudding, as J. J. Thomson once remarked when asked about the structure of the atom. As a whole the atom is neutral, the sum of all the negative charges of the electrons being equal to the positive charge of the sphere. Furthermore, according to Thomson, the electrons must be located symmetrically inside the atom, though external effects may cause them to shift or oscillate about positions of equilibrium. The loss of one or several electrons by an atom leads to the appearance of a positive current.

At first glance this concept of atomic structure should appear to suit both physicists and chemists and the "raisin pudding" could well have remained uncut for a long time. However, despite its simplicity, or perhaps because of it, Thomson's atom left many questions unanswered. For one, it was hard to imagine what the "pudding" itself —the atomic sphere devoid of electrons—represented. It seemed logical to assume that it contained particles like electrons, only oppositely charged.

Therein lies the logic of development. The appearance of the first elementary particle conjured others to life. Actually, the first step toward the discovery of a positively charged "raisin" had been made shortly before Thomson's model appeared. Simply the two theories had to evolve for a certain time along parallel lines before merging and budding forth in a new quality as Niels Bohr's atomic theory.

After a careful study of Roentgen's works, the French physicist Henri Becquerel came to the conclusion that the fluorescence of the glass of the X-ray tube was the real source of the mysterious rays. From here it was but one step to the conclusion that other fluorescent bodies are capable of emitting X-rays of various intensity.

To verify his reasoning Becquerel took a substance known for its strongly expressed fluorescent properties when exposed to sunlight, wrapped it up in several layers of black paper and placed it on a photographic plate. If, he reasoned, the fluorescent substance emits X-rays they will pass through the paper and produce a dark spot on the plate. If there are no such rays the plate will remain unexposed.

The result of the experiment surpassed Becquerel's expectations. When he developed the plate he found a clear imprint of the salt crystal. How was he to know at the time

that the crystal of uranium salt (double sulphate of uranium and potassium) which he was studying contained the embryo which was to bring to life the atom bomb, atom-powered ships, atomic electric stations!

It is said that if the weather had been good at the time the nuclear age would never have begun. This, of course, is not so. The progress of science does not depend much on chance, and many great discoveries were not so much the work of chance as their contemporaries and subsequent generations would have us believe. Be that as it may, but clouds kept the sun from peeking into the windows of Becquerel's laboratory. In expectation of the day when the sun would come out to induce fluorescence in his bit of uranium salt, Becquerel put the freshly wrapped photographic plate with the uranium salt crystal on it in the drawer of his desk. It is hard to say what induced Becquerel to develop the plate. Chance, perhaps? Or the subconscious instinct of a researcher?

The developed plate contained a clear image, not only of the uranium salt, but also of a coin that had been placed between the black paper and the crystal. The uranium salt had lain in a dark drawer and was quite incapable of fluorescence, yet the sharpness of the image was greater than in the initial experiments. The only conclusion was that the uranium salt emitted invisible penetrating radiation regardless of whether it fluoresced under the action of sunlight or not. This conclusion was made on the 26th February, 1896.

Our interest is in the milestones of subatomic discoveries, the discoverers of new elementary particles, the dates of birth of new bricks of the universe. But in its initial stages the history of man's penetration into the atomic nucleus is inseparable from the history of the atom. And this leads us to Ernest Rutherford.

ENTER THE NUCLEUS

The natural question following the discovery of different forms of natural radioactivity, was: What is the nature of this radiation? The first thing to do was to establish whether it carried any charged particles. This was accomplished by what has become a classical experiment with a magnet: a thin beam from a radioactive source is passed

between the poles of a strong magnet. If the particles are charged their trajectories are deflected by the magnetic field.

The radiation was found to consist of three parts. One beam, which bends a little bit, was called alpha radiation; the other, which bends more in the opposite direction, was called beta radiation; the third, gamma radiation, is not affected by the magnetic field.

The three types of rays were studied separately. They were found to be absorbed differently by various substances. Alpha rays are stopped by a thin sheet of paper. Beta rays can pass through several millimetres of aluminium. Gamma rays can be absorbed only by thick lead shields.

Then it was found that alpha rays represent a stream of fast-flying positively charged particles some 7,000 times heavier than electrons, which form the beta beam. It is because alpha particles are so much heavier than electrons that their beam is only slightly deflected in the magnetic field.

The first study of alpha particles was undertaken by Rutherford. He placed a bit of radium in a double-walled glass vessel with the air evacuated from the space between the walls. Alpha particles emitted by radium dissipated a large portion of their energy in passing through the first wall and were unable to pass through the second barrier. After a while Rutherford tested the space between the walls and found traces of helium, the second lightest gas after hydrogen. Today we know that alpha particles are nuclei of helium atoms.

Alpha rays and beta rays cannot be called rays in the strict sense of the word, as they are streams of charged corpuscles. Only the gamma rays, which had exposed the photographic plate in Becquerel's experiment and were not deflected by the magnet, can be properly called so. Like Roentgen's X-rays, they are electromagnetic oscillations of very high frequency that propagate through vacuum at the speed of light.

The next step was to see how the radiation affected the atoms of "ordinary" nonradioactive substances. Rutherford placed a thin, almost transparent strip of gold foil across the beam and set up a screen of zinc sulphide to register alpha particles: every particle hitting the screen was expected to cause it to scintillate, i.e., emit tiny flashes of light that can be seen in the dark.

What could be gained from this experiment? In the first place, if the atoms of matter, gold in this case, were solid beads, would they repel the particles or prove permeable to them? If atoms resisted the particle flux then, apparently, the corpuscles would have to behave like a Brownian speck of flower pollen in a liquid and change their direction endlessly under the impact of hundreds and thousands of collisions. In that case alpha particles emerging from the gold foil would scatter at various angles.

However, the behaviour of alpha particles proved more complex and contradictory. Most of them passed through the foil without hardly deflecting, which seemed to indicate that atoms are permeable. On the other hand, some were deflected at very large angles indeed, and some even bounced right back. Very few, to be sure, but one couldn't help reckoning with them.

Recalling his first experiments with radioactivity many years later, Rutherford commented that the phenomenon observed was, perhaps, the most incredible thing he had ever encountered, almost as incredible as 15-inch gun shells being bounced back by a thin sheet of paper. After due reflection he came to the conclusion that the back scattering was evidently a result of a direct hit. Nor was the difficulty resolved by mathematical calculations, for they required that the system involved have the bulk of its mass concentrated in an infinitely small nucleus.

Nature had once again demonstrated that the keys to its secrets are never the same. The experiments seemed to indicate that the swift flight of some alpha particles is abruptly altered by more strongly positively charged particles. Moreover, the charge and mass of these unknown particles are so great that they are capable of hurling back alpha particles travelling at 20,000 kilometres per second.

What could this unknown adversary be? An atom? But in Thomson's atom the positive charge is evenly distributed throughout the sphere and it could not generate such a powerful repulsion force. The only conclusion possible was to surmise that the positive charge and mass of the atom are concentrated in an infinitesimally small volume as compared with the overall size of the atom. However, it took Rutherford another two years of painstaking work, bombarding many different targets, before his initial guess was finally

embodied in the new physical concept of an atomic nucleus occupying a negligible portion of the atom.

In effect, an atom is hardly more than so much empty space: if one envisaged an atom the size of the earth, its nucleus would be the size of a city square. Again, one cubic centimetre of tightly packed nuclei would weigh 114 million tons.

In 1902, Rutherford and Soddy established the laws governing the transformations of radioactive elements. By demonstrating how different radioactive substances after passing through a long series of decays and transmutations ultimately turn into lead, the scientists not only rehabilitated the guiding idea of alchemists but also toppled the concept of the atom as an elementary particle. The experiments with scattering of alpha particles made it essential for theoretical physics to evolve a new model of the atom. Now the proton couldn't help being discovered.

With a theoretical explanation of the deflections of alpha particles flying past the nucleus of an atom of gold it became possible to predict the angles of deflection of the bombarding particles and the points of the fluorescent screen that could be expected to be hit.

The tremendous precision of Rutherford's experiments made it possible for him to produce a new, planetary model of the atom.

Around a positively charged nucleus revolve electrons like planets around the sun. It is they that determine the chemical properties of a substance, since chemical reactions are based on the number of electrons an atom is capable of losing or receiving. The total number of electrons in an atom equals the total charge and is balanced by the positive charge of the nucleus, making the atom as a whole electrically neutral. The number of electrons spinning around the nucleus on different orbits is the atom's fundamental characteristic, its "atomic number", which determines the square occupied by an element in Mendeleyev's Periodic System.

Rutherford's ideas were further developed in the works of his great Danish pupil, Niels Bohr. When Bohr visited Moscow in 1961, the participants of a seminar at the Institute of Physical Problems greeted him with the verse, "This is the atom that Bohr built." Bohr had, indeed, built the atom, the atom of hydrogen.

Only one year after Thomson had enunciated his hypo-

thesis of the structure of the atom, Bohr's theory of the hydrogen atom ushered in a new era in atomic physics. It provided a satisfactory explanation of some of the laws governing hydrogen spectral lines and introduced the concept of electron shells.

Shortly after the theory of the hydrogen atom was made public Arnold Sommerfeld suggested a more sophisticated model according to which electrons could have circular or elliptical orbits. More and more the atom seemed to resemble a planetary system. But soon advocates of the analogy began to feel worried. The mechanics of the microworld turned out to be much more complex than celestial mechanics, and each new confirmation of the "planetary" nature of the atom was at the same time a manifestation of peculiar properties incompatible with anything else known. Bohr's atom grew more and more complex. In 1925, Uhlenbeck and Goudsmit enunciated their hypothesis of the spinning electron to explain certain properties of the electronic structure of alkali metals. Today we know that all electrons spin, irrespective of whether they are free or bound with atoms.

At first glance it might seem that such a property as an electron's axial rotation should have meant a triumph for the analogy drawn at the beginning of this century between the solar system and the atom. Dialectics, however, teaches us otherwise, and its laws have been brilliantly confirmed in the history of the atom. At first, taken individually, the different states of the electrons constituting the atom shell did not seem to contradict the planetary concept. But when all the electron states were theoretically established and characterized by certain numbers (which physicists call quantum numbers), a new property appeared. It was defined in Pauli's famous exclusion principle, which states that no two electrons within the same atom can have all four quantum numbers the same. There is nothing of the sort in celestial mechanics. The analogy between the micro- and macrocosm is purely superficial and should be treated as such. In the same way, no one ever treated literally Thomson's atom as a "pudding" filled with tiny negative "raisins". It is useless to seek duplicates of our terrestrial concepts in either the world of infinitely large objects or the microworld. Each system has its own laws and, as we shall see later on, even time runs differently in different systems.

But the world is one, and thousands of invisible, intricate threads of not readily observable causal links extend from the tiny atom to gigantic sparking stars and remote galaxies. We shall return to the electron and its orbits again and again, for even information about stars contained in their rainbow spectra is deciphered thanks to atomic theory.

At present, however, we are primarily interested in the atom's nucleus. It was born in mystery and remains mysterious despite the fact that physicists have uncovered many of its secrets. The radius of the nucleus is smaller than that of the atom by a factor of 10,000, yet it contains almost all the atom's mass. It is first and foremost a concentration of matter. Do you remember how much one cubic centimetre of nuclear substance weighs? Therefore, it was the nucleus that had to be assaulted if the secrets of matter were ever to be unravelled.

But first let us make a small digression that will take us a little bit ahead.

Direct confirmation of the existence of the atomic nucleus was obtained in 1911, when it became apparent that it is the nucleus that emits beta electrons. The principle of beta decay, however, still remained a mystery. It had been assumed, by analogy with Thomson's pudding, that the electrons simply exist within the nucleus and in the space around it. Then the discovery of the neutron finally evicted the electrons from the nucleus. But it could not save the theory of beta decay from an impasse. The mechanism of electron formation remained a well-guarded mystery. In 1934, Enrico Fermi suggested that at the moment of radioactive transmutation an electron is suddenly created in the nucleus and ejected as a beta particle. Fermi's hypothesis that beta decay is associated with the production of particles of matter was, naturally, clothed in mathematical formulas and defined in terms of quantum theory. Not only did it offer an explanation of beta decay; it also predicted the possibility of nuclei ejecting positrons instead of electrons. This was subsequently brilliantly confirmed in works on artificial radioactivity.

Physicists know that theories which offer good descriptions of the microworld usually embrace a wider range of problems than their enunciators had initially envisaged and are frequently fraught with unexpected surprises. We shall see later on that Dirac's theory of the electron subsequently

yielded the first anti-particle, and Fermi's beta-decay theory produced the neutrino.

The purpose of this digression was to show that the development of a scientific idea is like the growth of a tree: not only the top, but the lower branches, too, throw out shoots. And, as in the Brazilian mangrove tree, a common shoot may join widely separated branches.

THE SECOND "BUILDING BLOCK"

The simplest nucleus is, obviously, to be found in the lightest atom—hydrogen. It is 1,836 times heavier than the single electron spinning around it. The nuclei of all other elements are heavier, and the next in order—that of helium—is four times as heavy. The mass of a nucleus of uranium, the last of the natural elements in the Periodic Table, is 238 times that of little hydrogen.

The mechanism of radioactive decay was first explained in 1913 by Fajans and Soddy, who introduced into atomic science what has come to be known as the Fajans-Soddy displacement law. What is this displacement?

When the nucleus of a radioactive element emits an alpha particle the particle carries off two units of charge and four units of mass, thus resulting in the formation of a new element two steps to the left in Mendeleyev's system.

In beta decay an atom's mass hardly changes, but as it loses a negative particle it acquires an additional positive charge and moves one step to the right.

Investigation of different types of radioactive decay literally forced physicists to the conclusion that there must exist some very important and at the same time very simple relationship between a nucleus' charge and mass. It is curious to note that this relationship could well have been discovered a hundred years before Rutherford's experiments. Already then, when the atomic weights of various elements were being determined more or less accurately, many researchers were greatly intrigued by the law according to which these weights increase from element to element. It seemed only natural to take the atomic weight of hydrogen for unity and then the atomic weights of other elements would be integers.

In 1816, William Prout, a London physician, wrote that, if the atoms of all chemical elements were primary funda-

mental particles and genuine "building blocks" of the universe incapable of being broken into fragments and completely unrelated to each other, why should an atom of nitrogen be exactly 14 times as heavy as an atom of hydrogen, and an oxygen atom exactly 16 times heavier?

It was apparent to Prout that the atom was not an elementary particle, to use the modern expression, with the exception, perhaps, of the hydrogen atom, out of which all others are built. Prout's idea could have substantially accelerated the advent of the atomic age, it could have completely overturned contemporary notions concerning the structure of matter. It could have.... But the laws of development are such that an idea that comes before its time is refuted by the subsequent advance of science.

More exact measurements of atomic weights revealed that they were not in fact multiples of the hydrogen atom and that in some cases the difference was considerable. At the time there was no satisfactory explanation capable of reconciling Prout's law with the observed deviations from integers. It is hardly surprising that his penetrating guess was forgotten. When it did reappear again in the natural course of events it was at a higher stage in the spiral of science, enriched with new discoveries and, of course, important changes.

Rutherford demonstrated that atomic nuclei are heavy, positively charged particles. They could not, however, be regarded as comprising hydrogen atoms since the charge and atomic weight coincide only in the case of hydrogen. For all other elements the charge is much smaller, and in the case of uranium, for example, it is only 92 for an atomic weight of 238. Evidently the nucleus contained something else besides hydrogen nuclei. Physicists tried developing a model of the nucleus with the available "building blocks", without resorting to new particles. This soon became a favourite method and, as we shall see later on, an erroneous one. It was postulated that the nuclei of all atoms are made up of hydrogen nuclei, the number of which equals the atomic weight. But in addition to the positively charged hydrogen nuclei, there were also electrons which cancelled out the excess positive charge.

This theory could explain all the known facts. More, it was supported by observable beta decay, in which electrons were emitted by the nuclei of radioactive elements.

The theory was additionally confirmed by the discovery of isotopes. Thanks to the works of Aston, it was established that most elements represent mixtures of several modifications of atoms of different mass. Modifications of atoms of the same element were called isotopes, and all the isotopes of a given element have the same atomic number or, in other words, the same number of electrons, and hence the same chemical properties.

But when the atomic weights of pure isotopes were determined a remarkable fact was discovered: they all proved very nearly whole numbers. For example, chlorine, whose atomic weight is 35.457, was found to be a mixture of two isotopes of atomic weights 34.978 and 36.977; copper comprised two isotopes of atomic weights close to 63 and 65. If one neglected the words "very nearly", Prout appeared to have been right. The physicists did as much, and the theory that the nuclei of all elements are made up of hydrogen nuclei triumphed. These nuclei, each carrying an elementary positive charge, were called "protons". However, it still remained a purely speculative hypothesis which required experimental confirmation.

In 1919, Rutherford bombarded nitrogen atoms with alpha particles and established that nuclei emitted protons. Other researchers later also observed the emission of protons by the nuclei of other elements. Thus, that protons are a component part of the nuclei of different elements was established experimentally, and the proton could thus be treated as an elementary particle—the second "building block" of the universe.

Here is the first nuclear reaction which opened the era of artificial transmutation of elements:

$$\mathrm{He}_2^4 + \mathrm{N}_7^{14} \longrightarrow \mathrm{F}_9^{18} \longrightarrow \mathrm{O}_8^{17} + \mathrm{H}_1^1 ,$$

where He_2^4 is an alpha particle (a nucleus of helium), N is nitrogen, F is fluorine, O is oxygen, and H is a proton, which we shall in future denote by the symbol p.

"NITROGEN CATASTROPHE", AND MORE TO COME

The years following the discovery of the proton were a time of brilliant experiments and stubborn quests, a time of the youth of atomic theory, which culminated in the creation of quantum mechanics.

In 1911, the Englishman Charles Wilson suggested an extremely simple method for directly observing charged particles. From then on physicists obtained tangible proof of the reality of the particles they had "invented" in the shape of photographs of cloud tracks left by them as they passed through the so-called cloud chamber. Experimental opportunities multiplied immeasurably. It became possible to observe the transformations which alpha particles, protons and electrons undergo, to count individual particles.

But the theory of an atomic nucleus comprising protons and electrons had hardly begun to take root when its creators began to have doubts. This was not a question of premonition or intuition. It was all much simpler and at the same time more complex. The physicists understood that electrons could not be allowed inside the nucleus, though without them it seemed impossible to explain its structure. It was an agonizing struggle, a stubborn quest for the most correct, though far from simplest, road.

Take, for instance, Rutherford's reaction. The atomic weight of nitrogen is 14, its charge is $+7$. Consequently its nucleus must have 7 protons. But what about the "extra" seven units of mass? And if it is assumed that the nitrogen nucleus contains 14 protons and 7 electrons to cancel out the excess 7 units of charge, quantum mechanics rebels against this. For it follows from quantum mechanics that it is extremely difficult for an electron to feel comfortable in the small volume occupied by the nucleus: an electron orbit is of atomic, not nuclear (10^{-8} cm) dimensions. But even this could have been accepted if not for a more important consideration.

In order to understand the physicists' difficulty we must examine the important property of elementary particles known as **spin**. Many particles possess spin, which is one of the four known "quantum properties" of elementary particles. It follows from the laws of quantum mechanics that for many purposes it is convenient to visualize a particle as a spinning top. This picture on the whole correctly conveys the symmetry of motion (notably the law of conservation of momentum, which accounts for a top's stability), but it cannot be reduced to conventional properties of motion of classical mechanics (rotation around an axis). Spin is a new quality peculiar to the microworld. The angular momentum, or spin, of a particle cannot possess just any value. It must

always be a multiple of the unit of spin, $\hbar=\frac{h}{2\pi}$, where h is Planck's constant, equal to 6.6252×10^{-27} erg. In these units spin can only be equal to 0, $\frac{1}{2}$, 1, 2, 3, etc. When two particles join to form a single more complex one (though no one can say what elementary particle is simple and what is more complex), their spins add up. If the spins were equal in magnitude but opposite in sense the resultant angular momentum of the new particle would be zero. Of such a particle it can be said that it has no spin or that its spin is zero. If the directions of the spins coincide and are, for instance, $+\frac{1}{2}$ and $+\frac{1}{2}$, the resultant spin is unity. That spin is a very important characteristic of elementary particles we shall see later on. At present it could be noted that the properties of particles with spin equal to $\frac{1}{2}$ (electrons, protons, neutrons) differ significantly from those of particles with unity spin (pions).

The spin of an elementary particle, unlike, for example, the rotation of a molecule, is an immutable property. An electron cannot be kept from rotating, and the rotation can be neither retarded nor accelerated. Spin, in fact, is so much an integral property of a particle that it cannot be altered without destroying the particle. To put it more precisely, if we could make a particle to spin faster we would get a new particle.

The moment of momentum of a single particle is, obviously, very small. As you flip the pages of this book your moment of momentum is no less than 10^{33} times greater than that of an electron. A comparison between the momentum of an electron and that of a human being is quite legitimate. The principle of quantization of spin is as valid in our world as in the microworld. The only difference is that the effect of quantization is so negligible that it simply cannot be measured for a large object. After all, it can hardly matter whether our moment of momentum is 10^{33} or $10^{33}+1$. It is quite impossible to register such a negligible increment and it is clear therefore why quantum properties were discovered not in the world surrounding us but in the world of atomic particles.

It is, perhaps, useful to say some more on the rotational motion of particles, or rather on the restrictions which quan-

tum mechanics imposes on such motion. The axis of rotation of every particle may assume only certain definite directions with respect to an applied external field. A particle with spin $\frac{1}{2}$ can assume only two positions, in which the axis of rotation is directed either along or against the field. Particles with spin 1 can assume three positions, with the axis of rotation directed along the field, perpendicular to it, or against it.

Another important characteristic of particles determined by their spin is known as its "statistics". Electrons, protons and neutrons (as well as all other particles with spin $\frac{1}{2}$) obey the Pauli exclusion principle, which states that two particles of a kind cannot occupy the same quantum level. Thus, in an atom each orbit can hold only one electron rotating in a given direction. Particles obeying the exclusion principle are said to be governed by Fermi-Dirac statistics, and are accordingly called fermions. Particles whose spin is an integer, which do not obey the Pauli principle, are said to be governed by Bose-Einstein statistics, and are called bosons.

We can now get back to the problem of the atomic nucleus. If we persist on assuming that a nitrogen nucleus comprises 14 protons and 7 electrons (21 particles in all), the composite spin of nitrogen will be half integral (an algebraic sum of an odd number of halves). But the spin of nitrogen is known to be unity. This was the "nitrogen catastrophe".

We shall see later on that there were many such "catastrophes" which ended happily in the discovery of a new elementary particle. Maybe some day physicists will discover a new world law, which today could be formulated as an empirical rule: "Don't try to build the world using the materials known to you; nature is much more sophisticated." It required a new particle to resolve the nitrogen catastrophe. Its properties were predicted before it was found, physicists proceeding from the same considerations as a man solving a crossword puzzle. He knows the meaning of the word and even some of the letters. Similarly, physicists assigned the particle properties which could resolve the catastrophe by whatever name one called it: nitrogen, oxygen, krypton, or what have you. They postulated that the nucleus contains particles equal to the proton in mass but car-

rying no electrical charge. The notion of such a particle was so tempting that it was voiced in 1920 simultaneously by three physicists: Rutherford in England, Mason in Australia and Harkins in the United States. As the particle had to be electrically neutral, Harkins suggested a name for it: neutron.

It is not widely known, but the word "neutron" was first introduced by William Sutherland in an article printed in the English *Philosophical Journal* in 1902. He attached the same meaning to the neutron as Rutherford, postulating its structure to be a closely packed conglomerate of positive and negative charges cancelling each other out. He suggested that the neutron be denoted by the musical symbol "natural", with the electron denoted by a flat and the positive charge by a sharp. This symbolism was not accepted and was soon forgotten. And in any case, at the time there were no means of discovering the neutral particle. Only charged particles left tracks in the cloud chamber, and it was ten years before the neutron's turn finally came; even then it might well have remained undiscovered if not for one strange case.

THE NEUTRON DISCOVERED

In a series of experiments the German physicists W. Bothe and H. Becker bombarded several targets made of different elements with alpha particles. When they were working with light elements—lithium, beryllium, boron-they observed a strange phenomenon: the bombarded targets began to emit a weak but extremely penetrating radiation which easily passed through screens that stopped alpha particles, gamma rays and X-rays. For the next two years many researchers repeated the Bothe-Becker experiment, but were unable to establish the nature of the penetrating "beryllium radiation", as it was called.

Irène Curie and her husband Frederic Joliot tried placing a paraffin screen on the way of the rays. Paraffins are hydrocarbons the molecules of which are straight carbon chains with attached atoms of hydrogen. In passing through the paraffin the mysterious radiation knocked the nuclei of hydrogen atoms—protons—out of it. This was a significant observation which, one could say, marked the beginning of radiation chemistry and even radiation genetics. At the

time, however, physicists were concerned solely with the nature of beryllium radiation. The young French scientists' experiment showed that the radiation possessed very high energy, as gamma rays had never knocked such fast protons out of paraffin. In spite of this, attempts were made to ascribe the properties of the new radiation to peculiar high-energy gamma rays. Such an explanation, however, inevitably led to an even more tangled knot of contradictions. Finally, on 27 February 1932, James Chadwick, after numerous experiments, voiced the idea that the Bothe-Becker radiation was not electromagnetic radiation but a stream of chargeless particles of mass closely approaching that of a proton. This was the neutron.

Chadwick correctly explained the new elementary particle's remarkable penetrating ability by the absence of electric charge, thanks to which they pass through an atom without interacting with the electrons.

Soon after Chadwick's discovery neutron emission was found in the alpha-particle bombardment of other elements. The neutron became a legitimate inhabitant of the atomic nucleus.

With the neutron's discovery the beryllium mystery ceased being a mystery and became a simple equation of an $(\alpha,\ n)$-reaction:

$$Be_4^9 + He_2^4 \longrightarrow (C_6^{13}) \longrightarrow C_6^{12} + n_0^1$$

where n_0^1 is a neutron of zero charge and unity mass number. The simplicity of the equation belies the amount of work and ingenious devices employed by Chadwick to unravel the picture.

Chadwick took polonium as a source of alpha particles placing a speck of it to a disk mounted in front of a beryllium target, all of which he placed in an evacuated box. The neutrons knocked out of the beryllium passed through the thin wall of the box and through a window into an ionization chamber connected, through an amplifier, with a recording device.

Neutrons have no charge and therefore are incapable of producing ionization in the chamber. However, when they hit the chamber's walls they eject charged nuclei which form ions in the chamber; they are registered by a turn of an electric counter or click in a loudspeaker.

When the neutrons knocked out of the beryllium penetra-

ted the chamber the counter registered only a few counts per minute. The count was not greatly affected even when Chadwick placed a thin lead screen before the chamber window. But when, instead of lead, he took a thin lamina of paraffin the number of counts immediately soared. The only explanation was that the neutrons striking hydrogen nuclei, which are equal to them in mass, knocked them out of the paraffin molecules. The charged protons flew into the ionization chamber, causing the rise in the particle count.

Thus the neutron joined the list of "building blocks of the universe". With its birth there was born a new branch of physics, neutron physics, progress in which eventually led to the practical utilization of atomic energy.

But the discovery of the neutron brought no peace. Rather the opposite. First of all it was necessary to review established notions about the structure of the nucleus. At first everything seemed to be all right. The theoreticians had even managed to remove the weakest link in the picture of nuclear structure, when it finally became apparent that there are no electrons in the nucleus. The basic component part of the nucleus, along with the proton, is the neutron. The new theory of nuclear structure was elaborated in 1932 by Werner Heisenberg and, independently of him, by D. D. Ivanenko and E. G. Gapon.

The atom was getting to be less and less like a pudding with raisins. According to the new conceptions, atomic nuclei are made up of protons and neutrons. The number of protons is equal to the total positive charge, that is the atomic number of the element, and the combined mass of the protons and neutrons is the atomic weight.

Thus, a nucleus of helium comprises two protons and two neutrons, and the charge is two and the atomic weight four. Revolving around the nucleus are two electrons which cancel out the charge of the nucleus, making the atom neutral. The existence of the neutron provided a fairly simple explanation of isotopes: the isotopes of one element differ in mass because their nuclei contain a different number of neutrons.

The new theory of nuclear structure swiftly won universal recognition. It satisfactorily explained the many facts that had been accumulated, indicated new experimental lines to be followed and threw open broad vistas for theoretical research. But from the moment this convenient and logical theory of nuclear structure was enunciated physi-

cists found themselves on the first step of a staircase leading into a maze. The deeper they penetrated into the atom the more puzzles confronted them.

The first to emerge was the mystery (how many times shall we use this word!) of nuclear forces. Placed in a nutshell, this mystery is: What holds the protons together in the nucleus?

The electrical forces, which cause a negative electron to be attracted by the positive nucleus, could be expected to scatter the protons in all directions. But far from scattering, protons stubbornly resist attempts to destroy the nucleus. Today we know what high energies are needed to crack the atomic nucleus. Obviously, here we have something unlike the forces of electrical attraction and repulsion. All the more so as the forces which keep the protons and neutrons together in the nucleus are much more powerful than electrical forces. Besides, how could an electrical force act on the chargeless neutron? Newtonian gravitation, too, offers no reasonable explanation as it is smaller than the nuclear binding forces by a factor of 10^{37}. The nuclear forces do not depend on the electrical charge of a particle. They possess the property of "charge independence", drawing proton and neutron, neutron and neutron or proton and proton together with approximately the same strength. On the other hand, nuclear forces have a very small radius of action. At distances of around 10^{-13} cm two protons are drawn together by a force 40 times exceeding their electrostatic repulsion. A fourfold increase of the distance makes the nuclear forces equal the electrostatic repulsion. Then, at distances below 0.5×10^{-13} cm the nuclear forces as it were alter their direction and transform into even more powerful forces of repulsion. What are these mysterious forces which appear as a new quality in going over from the atomic to the nuclear scale? Let us try to investigate the laws governing the electrostatic forces of the oppositely charged electron-proton couple. But first we must once again take up the story of another veteran of the subatomic world, the photon, a particle which for long had occupied a very privileged position.

The photon was not at once classified as an elementary particle. There were many reasons for this. It seemed too unlike nucleons—the nuclear particles, protons and neutrons —or electrons. Its behaviour was often extremely strange and couldn't be predicted in advance. On colliding with an atom it might split into two photons or vanish without a trace. The electron seemed quite another matter. No one, for instance, had ever seen it vanish. Some even questioned whether there was any need in the photon at all. Light had long since been established to be a stream of electromagnetic waves which could pass through narrow apertures, skirt obstacles and reciprocally reinforce or cancel out each other. The undulatory motion of light was beautifully described by mathematical equations. Light was, in fact, one of the most elegant and ordered departments of physics.

Yet precious little was known of its true physical nature. As Daniil Danin aptly put it in his book, *The Inevitability of the Strange World*: "You notice that as soon as we begin speaking of the photon as an elementary particle heading the present-day list of 'prime elements' we are led away into the impenetrable thickets of eternal 'accursed questions' which science asks about nature. But this is not due to our carelessness. Simply in the world of elementary particles one cannot make a step without landing in those thickets. This is not the trouble but the attractiveness and temptation of the story of the dramatic quests for the 'prime elements of matter'."

We too are compelled to proceed not along the beaten path of historical narration in which each subsequent event is newer than the previous one but rather along a spiral, from time to time returning to the past or proceeding ahead to the "seemingly past".

Let us recall once again that in 1887 Michelson and Morley staged their classical experiment which demonstrated that the speed of light is independent of the direction of propagation.

Suppose on the earth and, say, Venus observation stations are built for measuring the velocity of a beam of light passing through them. Both stations will record the same result regardless of whether they are moving in relation to each other or not. Einstein adopted this very important

premise as a point of departure and decided to verify the conclusions deriving from it. The consequences of this rapidly outgrew the cause from which they derived and expanded far beyond its boundaries.

In 1905, Einstein published his celebrated article, *On the Electrodynamics of Moving Bodies.* Leopold Infeld, the well-known Polish physicist who had worked with Einstein for many years, gave an excellent description of this work:

"The title sounds modest, yet as we read it we notice almost immediately that it is different from other papers. There are no references; no authorities are quoted, and the few footnotes are of an explanatory character. The style is simple, and a great part of this article can be followed without advanced technical knowledge. One can only wonder that this work, so different in form from the ordinary run of research papers, was passed by the reviewer (if there was one). This is all the more remarkable as its full understanding requires a maturity of mind and taste that is more rare and precious than pedantic knowledge. Even today its presentation and style have lost nothing of their freshness. It is still the best source from which to learn relativity theory. Its author was an outsider, not even a member of the scientific profession. He was, in 1905, a young Ph. D., twenty-six, and a clerk in the Patent Office in Berne, Switzerland."

Although in the special theory of relativity Einstein postulated that *all laws of nature are the same in all inertial co-ordinate systems moving uniformly in a straight line relative to each other*, this did not mean that the classical laws of physics should be regarded as absolute. When the problems raised by the ether were being debated it already became clear that classical mechanics was incapable of explaining a number of phenomena deriving from the motion of bodies at velocities approaching the speed of light. It was therefore necessary to change many physical laws, giving them a form which would correspond to Einstein's postulate.

Imagine a laboratory completely isolated from the outside world. This isn't hard, is it? Well, no experiment carried out in this laboratory is capable of detecting its uniform rectilinear motion with respect to the fixed stars. This, perhaps, could appear obvious even without the relativity theory. But if we now imagine that our isolated laboratory

starts rotating with respect to the stars it is equally apparent that the experimenter inside will notice it at once. Einstein's principle is not at all so apparent; rather it is remarkable.

Einstein extends the principle of relativity to all the laws of nature (in the first place to the laws of electromagnetic phenomena) and thereby immediately explains the negative result of Michelson's experiment as an obvious corollary of relativity theory.

Uniform rectilinear motion with respect to the fixed stars affects nothing, hence on the moving earth the light rays in Michelson's set-up behave just as they would had it been at rest.

An analogy can be drawn with passengers playing pool in the saloon of a smoothly sailing ship. They will see no difference in the motion of the balls whether they are shot in the direction of the ship's motion or at right angles to it. The ball rolling across the table "doesn't know" which way the ship is moving and bounces with equal ease from one side to the other regardless of the ship's course. The players as a result have no way of determining whether they are playing on board a ship or in a hall on solid ground.

If the billiard table is likened to Michelson's set-up, the balls are likened to beams of light, and the ship to the earth, the experiment will take place in exactly the same manner as if the earth was at rest with respect to the fixed stars. Like the billiard balls, the light beams are completely indifferent to the angle with respect to the earth's motion at which they are propagating.

The enunciation of new laws deriving from the mechanics of sub-light velocities was no easy task. In the first place they had to present a correct picture of all known phenomena. Furthermore, and perhaps the most difficult thing of all, it was necessary to undertake a complete review of some of the fundamental concepts of mechanics, such, for example, as the definitions of force, mass and acceleration.

At this stage Einstein had some freedom of choice, but his choice was always in the direction of simple mathematical forms. The essence of his theory can be set forth in relatively simple terms.

1. Newton's formula stated: "Absolute, true, and mathematical time, of itself, and from its own nature, flows equably without relation to anything external." After Einstein's postulates it is no longer possible to claim that ev-

ents take place at a given absolute time. Also devoid of absolute meaning is the concept of simultaneity. It is impossible to say for sure which of two events precedes the other if they occur at different places. The answer to this question depends wholly on the position of the observer, on how far or close he is from the places where the events take place. The meaning of this proposition can be visualized when one realizes that it is impossible to receive the information about the events instantaneously, insofar as the messenger—a light signal—travels with finite speed.

2. Just as we have rejected the concept of "absolute time", so we must reject the concept of "absolute space". For in fact, while one observer may declare with full confidence that two events have taken place at the same point in space, only at different times, another observer may declare with equal right that the events occurred at different points —that is, if he was in motion relative the first observer at the time. Space and time are linked together by the firm bonds of relativity. It is possible to speak of time as of a fourth coordinate, a "fourth dimension" of space. In fact, it would be more correct to speak of space-time. The movement of different forms of matter takes place in space, while consecutive changes in their qualitative states take place in time. Therein lies the difference, as well as the dialectical unity and inseparability, of moving matter and the forms of its existence: space and time.

3. Einsteinian mechanics states that the mass of a moving body is greater than its rest mass. Motion imparts to a body a mass increment which is the greater the greater the velocity of motion. The famous equation of the nuclear age, familiar even to people extremely remote from physics, $E=mc^2$, is an expression of one of the profoundest laws of nature. The "rest" mass inherent in a body at rest is also associated with a certain amount of energy.

Photons possess no rest mass. They are always travelling at the speed of light and their mass manifests itself solely in motion. One could say that they exist only because they move. No body, no elementary particle can travel at a speed exceeding that of light. Photons travel in vacuum at the velocity $c=299{,}776$ kilometres per second. This is the greatest velocity. If a body's speed begins to approach c its mass increases sharply. That is why, when people speak of the mass of an elementary particle, they presume its

rest mass. Mass and energy are equivalent. By increasing the energy of particles in an accelerator we at the same time increase their mass, and physicists frequently express a particle's mass in units of energy.

Finally, not only the laws of mechanics are subject to reviewal, but Newton's law of gravitation as well. But this will be discussed elsewhere.

BRIEF EXTRACTS FROM THE CODE OF STRANGENESS

It will be recalled that five years before Einstein uttered the word "photon" the word "quantum" had appeared. In 1900, Max Planck postulated that energy is absorbed in batches, which he called quanta. A batch smaller than a quantum simply does not exist. If the atom was once thought to be the limit beyond which matter could not be fragmented, the quantum became such a fragmentation limit for energy. Subsequent advances of quantum mechanics made it much more general and comprehensive than its creator had ever imagined.

Today it is as unthinkable to describe subatomic processes without quantum or wave mechanics as without relativity theory. There is quantum statistics and quantum electrodynamics, and now quantum chemistry has appeared.

Planck studied the energy distribution of the heat radiation, emitted by hot bodies, according to wavelengths. He found that the distribution curve has a clearly defined hump or peak. This contradicted the notions of classical mechanics, according to which in the region of very short wavelengths the distribution curve should approach infinity. Planck himself treated the idea of the "granulation" of energy as no more than an ad hoc hypothesis capable of explaining the unexpected behaviour of the distribution curve. Nevertheless, he formulated his famous postulate: The energy of an oscillation source (in the atomic domain) does not change continuously and can have only specific values, that are multiples of $h\gamma$, where γ is the oscillation frequency and h is the constant mentioned before. According to Planck, the emission or absorption of radiation is accompanied by jumps from one "energy level" to another. A jump from a higher to a lower energy level is accompanied by radiation. Absorption causes a jump from a lower to a higher energy level.

Jumps are always accompanied by either the absorption or emission of energy quanta $h\gamma$. The proposition that radiation is emitted discretely by impulses contradicted all existing notions of light and other forms of electromagnetic radiation propagating as continuous sequences of waves.

Einstein used Planck's concept of energy quanta. He pointed out that the quantum nature of energy exchange between matter and electromagnetic radiation can be substantiated with data deriving from investigations of the photoelectric effect.

The experimental proof of Maxwell's idea that light propagates like electromagnetic waves was provided in 1888 by Heinrich Hertz. Later, in experiments in which an electric spark was made to leap through the air gap between the two spherical electrodes of a vibrator, Hertz observed that when the gap was bathed in ultraviolet light it transmitted electric current better.

In the latter eighteen-eighties there appeared A. G. Stoletov's fundamental work, *Actino-Electric Investigations*, which set forth the basic laws of the photoeffect, later confirmed to a great degree of accuracy.

Stoletov's experiment (carried out at about the same time as experiments on the photoelectric effect by Hallwach) is extremely simple: he irradiated metal lamina with ultraviolet light and registered electric current in a broken circuit. The ultraviolet light, it turned out, knocks negative electric charges, called photoelectrons, out of the metal.

Einstein used the quantum concept to explain the photoelectric effect. Each electron is knocked out of the metal by a separate light quantum, or photon, which loses all its energy in the process, a portion of it to break the electron's bonds with the metal. Einstein showed the dependence of the electron's energy on the frequency of the light quantum and the electron's binding energy with the metal.

The story of the photon could, it would seem, be completed, but as has all too frequently been the case, the appearance of a new elementary particle, while solving one riddle, immediately created another. The photon was no exception. Although the photon seemed to possess corpuscular properties (in 1889 P. N. Lebedev even demonstrated the existence of light pressure) it was possible to determine the energy of a particle of light only by representing it as a wave of certain length and frequency.

So what is the photon, a wave or a particle? The answer is both. It has no rest mass and cannot be measured in linear units. The very properties which distinguish the photon from other particles, namely its apparent wave properties, at the same time relate it more closely to the indigenous inhabitants of the microworld. This was aptly put by Louis de Broglie: "Why, if wave matter possesses corpuscular properties, are we not justified in expecting the reverse: that corpuscular matter may display wave properties? Why may there not be a law the same for all material formations, whether wave or corpuscular?"

If de Broglie is right this means that every substance, like radiation, is endowed with a certain periodic wave phenomenon dependent solely on the mass and velocity of the body.

In 1927, the Americans Davisson and Germer and Englishman G. P. Thomson confirmed de Broglie's hypothesis by discovering electron diffraction. Fast electrons passing through metal foil behaved like light passing through small apertures or narrow slots.

Later diffraction was discovered in more "substantial" particles: protons, neutrons, atoms, and even molecules.

This was a signal event. Two such apparently contradictory theories as the corpuscular theory of undulatory matter and the wave theory of corpuscular matter merged in a unified quantum mechanics. Out of this union was born a new quality without which a definition of an elementary particle would have been impossible: the wave-corpuscular duality of elementary particles, according to which they are not quite particles but particles *and* waves concentrated within a specific domain of space.

At long last some semblance of order seemed to have been established in the microworld. However, it was an order amid strangeness. The revolutionary ideas of de Broglie, Schrödinger, Dirac and Heisenberg resulted in such a comprehensive synthesis of all quantum phenomena that the physicists' last doubts were dispelled.

Still, the ideas seemed too revolutionary for everyone's comfort. The properties of subatomic entities were completely without parallel in the conventional world about us. In the first place, it was necessary to part with such an apparently necessary attribute of motion as trajectory or path. A thrown stone describes a parabola. However tricky the path

of a powerfully driven billiard ball which lands in the pocket after several collisions with other balls and the sides of the table, it can be traced after all. Even the mote of flower pollen in the famous experiment that illustrates Brownian movement possesses an inimitable path of its own.

But elementary particles, moving according to the laws of quantum mechanics have no definite path in the conventional sense of the word. This is, of course, rather hard to imagine when the word "electron" or "proton" conjures up in the mind a picture of a tiny bead, a particle. But one should always remember the duality of particles, their wave properties. A wave spreading out into infinity simply cannot have a path, which is a characteristic of corpuscular, macroscopic bodies.

An interesting picture can be observed when a thin lamina is bombarded by individual electrons. The electrons hitting a screen set up behind the lamina reveal themselves by scintillation at different points, suggesting that they hit it as particles. But when their distribution on the screen is investigated it is found that they form concentric circles with alternating fringes of rarefaction and density. The distribution pattern obeys wave laws.

This synthesis of contradictory wave-corpuscle properties in subatomic entities should not be taken literally, mechanically. To say that these entities are simultaneously particles and waves is to say nothing. Their essence is better defined as neither particles nor waves but rather a dialectical unity of the properties of both.

It is only natural to expect qualitatively new properties to manifest themselves in this domain. The movement of elementary particles in space and time cannot be equated to mechanical forms of motion. For example, it is impossible to define the position of an elementary particle in space at every given moment with the help of a coordinate system as we do with familiar bodies. Particles move according to their own laws, described by the so-called wave function.

Proceeding from the ideas of de Broglie, the Austrian physicist Erwin Schrödinger elaborated a theory of particle motion taking into account their wave nature. He worked out an equation expressing the change of state of atomic systems with time and making it possible to determine

their wave function at any instant. By solving Schrödinger's equation one can determine, from a given initial state, the probability of a particle occurring in a given point of space at a certain moment of time.

Schrödinger's equation is, on the atomic scale, approximately what the laws of Newton are in classical physics. Werner Heisenberg discovered a curious corollary, which later became the cornerstone of quantum mechanics.

In dealing with conventional objects—a stone, bicycle, flying eagle—we can, at least in theory, state the law of motion. All we need for this are two quantities: the body's position in space and its momentum.

In the microworld things are different, and it is impossible to determine simultaneously and with absolute precision a particle's position and momentum. In the former case we could claim that the errors in determining the momentum and coordinates are zero; in the latter both errors cannot be simultaneously zero. The product of these errors, it was found, is approximately equal to Planck's constant h. And this is just what Heisenberg's celebrated uncertainty relation, enunciated in 1927, states: The product of the uncertainty of coordinates and uncertainty of momentum is greater than, or equal to, Planck's constant.

Complete precision is possible only with respect to one parameter, either the particle's position, or its momentum. And the more precision we insist upon in measuring the one the greater will the error be in the case of the other. A similar relationship exists for another "uncertainty pair", time and energy. One must truly be a six-armed Siva to undertake precision measurements of both the coordinates and momentum of a particle.

The strange behaviour of particles and the mysterious laws they obey are indications of the existence of some other, unknown, non-classical mode of causality governing events in the microworld. A study of the phenomena of that world has led to the discovery of a new, statistical, causality which governs the movement of elementary particles.

Classical physics proceeds from the assumption that an experimenter setting about to investigate a system of bodies knows everything about the forces applied to it. Only then can he hope to predict the system's behaviour at every point in space and in any interval of time. Thus, astrono-

mers can predict with great exactitude the positions of planets and stars for many years ahead. On the other hand, should the celestial harmony be disrupted by the sudden appearance of a new planet or star the astronomers would have to concede the failure of their predictions.

An event can be predicted if the system with which we are concerned is not involved in any unforeseen interactions, if it does not come into contact with other, unknown systems. In classical physics such a system is called isolated, though strictly speaking there is no such thing: in our world all things inevitably come into contact and interact with other things. But as long as a researcher is dealing with macroscopic entities for which unforeseen effects are negligible, he can treat his system as isolated to a high degree of accuracy. Obviously, a schoolboy studying heat transfer from a hot body need not take the sun's radiation into account: it remains outside his closed, isolated system. In more exact experiments the sun must be included in the system, but the stars can be neglected. Obviously, all things cannot be foreseen, but neither is this necessary. A weather man studying atmospheric currents will not take into account air movements caused by people breathing or, say, a housewife beating a carpet. These effects are virtually outside his system as they are too small to influence it one way or the other.

But as soon as we turn to the world of elementary particles the conditions change entirely. Unlike the case in classical mechanics, the state of every elementary particle is enormously dependent on the states of the particles around it. Using the concepts of classical physics, every particle is a completely non-isolated system and its behaviour depends first and foremost on its interactions. And as it is impossible to take all or most these interactions into account the result is a "nonclassical" causality in which all kinds of complications and disruptions inevitably occur in the idealized picture which would have agreed with classical causality.

The laws of the microworld are derived from studies of certain aggregates, sets, or ensembles of particles and their properties. The members of an ensemble are closely associated, they interact, exchange places, reciprocally transmute, vanish into one another and appear one out of another. An ensemble thus acquires a new quality as com-

pared with a separate particle, which finds expression in the peculiar statistical character of its laws, which are incapable of reflecting the properties or behaviour of individual members with sufficient accuracy. They only make it possible to determine their probable, possible positions and states.

The first type of interactions between individual particles was established and studied for the electron and photon. At first it was very simple. Coulomb's law, enunciated back in 1784, states that the force acting between two electric charges is in reverse proportion to the square of the distance between them. Thanks to the works of Faraday and Maxwell it was established that a change in the electrical forces between charges propagates not instantaneously, but at the speed of light. If the distance between charges is altered and one is moved away, the other will "feel" the decrease in electrostatic force in the time interval needed for a light quantum to span the distance between the charges.

Interactions between electrical charges are effected by photons. An electromagnetic field represents photons continually emitted and absorbed by a charged particle. Theory explains the behaviour of electrons in electromagnetic field, assuming that every electron continuously produces and absorbs photons. Such pulsations are the means whereby field and electrons interact.

This is the main type of interaction in quantum electrodynamics. The emission and absorption of photons is a vivid example of what is called a virtual process. It is a conception characteristic of quantum mechanics and it extends to all particles without exception. A virtual process presumes an apparent violation of the law of conservation of energy. To understand this it should be remembered that a photon possesses energy, and when an electron spontaneously emits a photon an apparent sudden increase occurs in the total energy of the system. Quantum theory easily skirts this submerged rock. The point is that the photon is emitted and reabsorbed so quickly that the increase in energy cannot be detected by any means, even in principle. But once a virtual photon cannot be detected the conservation law is not violated since, according to the principles of quantum mechanics, its laws are applicable only to observable quantities. The obvious question then

is whether virtual photons can become real photons? Certainly. Only for this an input of outside energy is needed.

Virtual photons take part in all interactions between charged particles and electromagnetic field. It is due to the virtual photon field that the electron is attracted to the proton. However, for protons the predictions of quantum theory are not so precise as for electrons.

The electron-photon scheme proved adequate for explaining many phenomena in the microworld. The existence of the electron and photon even seemed to completely describe the external properties of atoms: the observed charges of atomic nuclei and, somewhat less precisely, their masses could be explained by the existence of neutrons and protons.

The number of "building blocks" of the universe was now four.

A DROP IN "DIRAC'S OCEAN"

In 1928, Paul Dirac, an English physicist and pupil of Rutherford, was working on the theory of the electron. His idea was that it should be in agreement with all the requirements of relativity theory. His work was crowned by a beautiful equation describing the magnetic properties of the electron. But although the theory was in agreement with experimental data many scientists were apprehensive: it contained much too much strangeness.

According to quantum theory, every elementary particle possesses wave, and consequently frequency, properties (frequency is the inverse of wavelength). When Dirac's wave equation for the electron was solved it yielded both positive and negative frequencies. As in quantum mechanics frequency is proportional to energy ($E=h\gamma$) it was hard to explain the meaning of the negative solution. It required the genius of Dirac to reveal the concrete physical meaning lying behind the mathematical puzzle. He postulated the existence of electrons with negative energy and negative mass. When acted upon by electrostatic forces they would move in a direction opposite that which would have been taken by ordinary electrons.

They say Dirac approached his equation from aesthetic positions. "It is too beautiful to be wrong," he declared. Although aesthetic criteria are penetrating deeper into

science, and art is also a method of cognizing the world, it is unlikely that aesthetic considerations predominated in Dirac's thinking. He was not easily discouraged by the notion of negative mass. That this is so is illustrated by the following episode.

At an annual contest sponsored by the students mathematical society at Cambridge the contestants were offered the following problem to solve. Three fishermen were forced by bad weather to stop their fishing and find shelter on a small island. One of the men, unable to sleep, got up, divided the meagre catch into three equal parts, took his share and departed. True, when he divided the catch there was one extra fish which he tossed back into the water so that no one would be offended. Just before dawn another fisherman woke up and also decided to return home. Not suspecting that the catch had been divided, he divided the remaining fish into three parts and was also left with an extra fish, which he threw back into the water. Later the third fisherman repeated the whole operation, also with one extra fish. Question: How many fish were there in the first place?

Dirac's solution was paradoxical: minus two. This was the answer given by the young student. Formally he was right. Mathematics is not concerned with negative fishes.

It goes without saying that at the time terms like "negative energy" or "negative mass" were vague abstractions. No "negative" electrons, or anti-electrons, had ever been observed in nature, and physicists were in no hurry to recognize Dirac's "donkey electrons" as they were called. Dirac countered by enunciating a theory which came to be known as "Dirac's ocean".

Imagine that some electrons have landed on a negative-energy level. Then what we call vacuum will in fact be an infinite number of such electrons carrying various energy reserves. But the sum of the electromagnetic and gravitational fields of these electrons is zero. Trapped in this "ocean" of Dirac's electrons like bubbles of air in water are holes of space free from electrons. When an ordinary electron lands in such a hole a mutual annihilation of hole and electron takes place and they become photons possessing an equivalent amount of energy.

Reciprocally, if one manages to pack a sufficient amount of energy in a very small volume, as happens, for example,

when two fast moving particles collide, an electron-antielectron pair may be created.

As the antielectron had to possess a positive electric charge, some theoreticians sought to embody Dirac's abstract idea in the only known positive particle, the proton. But this hypothesis quickly stumbled into difficulties. Firstly, how could the proton and electron coexist together so long in atoms whereas Dirac's theory required the almost instantaneous destruction of the oppositely charged particles; secondly, what happened to the difference between the mass of the electron and that of the heavy proton?

Cosmic rays came to the physicists' help.

In the year 1932, an American physicist, Carl Anderson, was studying the tracks produced in a cloud chamber by cosmic rays when he discovered a track left by an unknown particle. When a cloud chamber is placed in a magnetic field the tracks of charged particles deflect one way or another, the direction indicating the particle's charge. The thickness of the tracks makes it possible to distinguish heavy particles from light ones.

The strange track differed in no way from electron tracks, only its curve was in the opposite direction, meaning that it was oppositely charged. This particle was the **positron**, and soon it was found that positrons can be obtained without the help of cosmic rays: electron-positron pairs can be produced in matter irradiated by gamma quanta. Some radioactive substances emit positrons spontaneously, like beta particles. The positron is an elementary particle identical to the electron but oppositely charged and possessing certain other properties to be spoken of later on. Unlike the electron, in the part of the universe known to us it occurs extremely rarely. This is because, on colliding, a positron and an electron mutually annihilate, breeding two or, rarer, one or three light quanta. An electron and positron can be produced or annihilated without any transmutations of the other particles taking part in the interaction. They can also appear and disappear in processes where photons are the only particles involved.

The energy of a quantum producing an electron-positron pair must equal the pair's combined mass times the square of the speed of light. As the rest masses of the electron and positron are very small, the pair can be produced even by the gamma radiation emitted by radioactive elements.

That is why the process, as well as the annihilation of the pair, was observed by physicists long before the first particle accelerators were built.

The production of an electron-positron pair can be observed in a cloud chamber with a metal screen placed across the path of a gamma beam. When a gamma quantum hits the screen it strikes an electron and a positron out and they spiral away in opposite directions under the influence of a magnetic field. As the two particles' masses are the same the cloud tracks left by their spirals are practically identical and a picture of them looks like the antennae of an insect.

The reverse process is the annihilation of an electron-positron pair, in which both particles vanish. As our world contains very many electrons it is hardly surprising that a positron encounters one very soon after its birth and is annihilated with it, turning into a light particle. A positron's mean lifetime is 10^{-10} sec. In the microworld this is not so little and, as we shall see later on, the positron can be regarded as a relatively long-lived particle on the atomic scale.

The appearance of the precomputed positron caused no appreciable headaches in the question of atomic structure. It reaffirmed the physicists' conviction that every strangeness has its material carrier. Paraphrasing the French *mot* with respect to the atom, one could say, *cherchez la particle elementaire*. If something is unclear, inexplicable or downright incredible—look for a new particle. As in the case of the neutron, which resolved the nitrogen catastrophe.

But even an idea has its peculiar, as yet unexplored conservation laws: in gaining something we always seem to lose something. The neutron introduced beauty and order into the nucleus, but it also bred numerous new questions.

For one, if there are no electrons in the nucleus, how does one explain beta decay, the spontaneous emission of electrons by the nuclei of radioactive elements? And the later discovered positronic beta decay? Perhaps a special theory is needed for radioactive nuclei?

However, unlike the case of the nitrogen catastrophe, "nuclear" electrons and positrons did not cause any major headaches. Quantum theory was a powerful tool in the theo-

reticians' hands capable of explaining the peculiar, "strange" properties of the microworld.

Nuclei do not, in fact, have any electrons or positrons. But they appear spontaneously in emission processes. It is like the emission of light by atoms. Until the very last moment there are no photons in the atom, but they suddenly appear at the right time. Recall the electron and virtual photons mentioned above. To be sure, the photon is less of a particle than an electron, which does have rest mass. But don't forget Einstein's great law. Mass and energy are equivalent and they may transform reciprocally into one another. And the production of an electron and a positron, with their very small masses, does not require much energy, which is always available in an atomic nucleus. This is all very well, but in addition to mass, which cannot be produced out of nothing, the electron and positron also possess charges, which also have to come from something. The source is again energy. And here the law of conservation of charge is maintained by the creation of two particles the algebraic sum of whose charges is zero.

This is the necessity inherent in strangeness! The positron simply had to exist, otherwise the physicists would have had to invent a particle with the same properties.... Not literally, of course, for physicists do not dictate nature its laws. These laws are a part of objective reality which man gets to know by all the means at his disposal.

THE ELUSIVE NEUTRINO

In 1934, Igor Tamm enunciated his famous theory of nuclear exchange forces. They appear between two interacting particles which exchange a third particle that transmits a certain quality from one particle to the other. The quality can be defined as that of identity. Identity between proton and neutron. This is to say that the theory of nuclear exchange forces presumes that a proton can change into a neutron and a neutron into a proton. With the arsenal of particles at the disposal of physicists in the 1930s one could visualize the exchange process as follows: on meeting a proton, a neutron, which consists of a proton and an electron, emits an electron, thus turning into a proton; the proton captures the electron and becomes a neutron. This can be written down as a reversible reaction:

$$n \rightleftarrows p + e^-$$

The reversibility sign denotes that the particles as it were exchange their properties, and this continuous exchange locks them together. Accepting this scheme, one can regard the proton and neutron as two states of the same nuclear particle, the nucleon.

No changes in the composition of the nucleus and no radiation occur in the exchange process. If, however, the nucleus is radioactive, and radioactivity is a property of unstable nuclei with an unbalanced proton or neutron ratio, the nucleons can transmute without the reciprocal exchange.

If neutrons predominate in the nucleus, stability is achieved through the transmutation of several neutrons into protons. The electrons produced in the process cannot remain in the nucleus and are thrown out as beta radiation. If there is an excess of protons some of them change into neutrons through the emission of positrons.

This is, of course, a simplified picture of the mechanism of nuclear exchange. According to the exchange forces theory radioactivity can be explained as a spontaneous urge of the atomic nucleus to achieve stability.

This explanation of the mechanism of nuclear decay with the emission of electrons or positrons could, in itself, have satisfied the physicists, if only one could neglect the energy aspect of the problem. It was here that the mystery lay which was to be resolved by the birth of a new elementary particle.

The energy of electrons emitted by an atom can be determined by measuring the magnitude of their deflection in a magnetic field. All the more so as, according to quantum theory, energy is emitted in uniform batches. At least the physicists were justified in expecting this in beta decay, since the emission of alpha particles and gamma quanta was found to obey very strictly the law of discreteness.

It was found, however, that the electrons emitted by the nuclei of a given isotope displayed a continuous radiation spectrum from zero to a certain maximum. This puzzling behaviour was further complicated by an utterly inexplicable loss of energy. The energy released in beta decay can be determined from other data which, apparen-

tly, should show it to be equal to the energy of the emitted electrons. In fact, however, the released energy was always found to be equal to the highest point of the spectrum curve, which would indicate that in actual fact the electrons carry off less energy than they should. Why? What happens to the balance? It worked out as if the law of conservation of energy did not apply to beta decay. And the law of conservation of moment of momentum or spin also seemed violated, as a portion of the spin had also vanished into thin air. This was a grave test. So grave indeed, that Niels Bohr went so far as to suggest that the law of conservation of energy simply did not hold.

The logic of events called for the "invention" of a particle whose properties would explain the paradoxes of beta decay. The Swiss physicist Wolfgang Pauli reasoned approximately as follows: If the characteristics of beta decay are incompatible with the conservation laws this means that the process has been incorrectly described. There must be some neutral unobserved particle taking place in the decay which carries away the lost energy and momentum. Furthermore, though in every process a definite total energy of all the particles involved is released, its distribution among the decay products is such that the electron receives different amounts of it on various occasions.

Thus, in beta decay the formula is not $n \rightarrow p+e^-$, but $n \rightarrow p+e^-+x$, where x is a neutral particle. Enrico Fermi called it a **neutrino**, which is the diminutive for "neutron" in Italian. Today this particle is called the **antineutrino**, the name neutrino being given to the particle involved in positron decay: $p \rightarrow n+e^++\nu$, where ν is a neutrino.

Today it is known that, like the photon, the neutrino and antineutrino lack rest mass, that they possess spin $\frac{1}{2}$ and thus belong to the fermion family.

The total energy of the electron and antineutrino equals the difference between the masses of the neutron and proton, but the electron's own energy may vary as its distribution varies from decay to decay.

Now everything seemed logical and orderly. The conservation laws had been salvaged by increasing the number of elementary particles. But one drawback still remained: after all, the new neutrino had been invented "at penpoint", theoretically, and its properties had been postulated but

not verified by experiment. This had to be done, but how? The neutrino is a remarkable particle. However poor our knowledge of the internal structure of nucleons, it is still immeasurably greater than our knowledge of the neutrino. We know absolutely nothing of its inner structure. Physicists are still arguing whether the neutrino and antineutrino are actually different particles, like the electron and positron, or one and the same, like left-polarized and right-polarized photons.

This is a point that deserves closer scrutiny. As light represents oscillations of electromagnetic field, one can speak of the direction of oscillation of the electric and magnetic vectors. A vector can oscillate only perpendicular to the direction of propagation of light, hence we have a choice of one of two possible directions.

An oscillation in planes can be represented as a sum of two rotational motions, one clockwise, the other counterclockwise. Hence two types of photons are possible. The movement of one can be compared to the symmetry of a right-handed screw, the other with a left-handed one. The former is a left-polarized photon, the latter is right-polarized. The atom emits an equal number of left- and right-polarized photons, which is why in nature they are evidently evenly distributed.

Photon polarization illustrated by analogy with a screw is like characterizing spin in terms of a top. Essentially, a screw *is* a top to which translatory motion has been added: it is a top travelling along its axis.

But to return to the neutrino. Its elusiveness is due not only to the absence of rest mass and charge but mainly to its incredible penetrating ability. In this respect it is without equal in the microworld. It is a champion particle, if not to say a ghost particle. It can pierce matter almost as easily as vacuum. It is said that a steel slab billions of times greater than the distance from the earth to the sun would be incapable of stopping it.

Twenty-five years passed between the "theoretical" birth of the neutrino and the experimental verification of its existence. In these years, as Academician Bruno Pontecorvo once remarked, some people seemed to have forgotten that the neutrino is a material entity and in principle observable, the difficulties with detecting it being temporary and due solely to the technical capabilities of the time.

As mentioned above, the free path of a neutrino through an absorber can be expressed by a figure with a tremendous number of zeros. This means that millions of billions of neutrinos would have to be passed through a kilometre of solid substance in the odd chance of detecting a single interaction. This apparently utterly hopeless task was solved.

A. I. Leipunsky suggested that the neutrino could be detected by observing the rebound of a proton, the speed with which it flies off. This speed should evidently vary depending on whether an electron alone or an electron together with a neutrino is emitted. In the absence of adequate experimental techniques Leipunsky was unable to carry out the experiment. It was only in 1948 that James Allen first performed it, though in spite of its beauty and precision the question of interaction of the neutrino with matter still remained unresolved. Physicists continued to be obsessed by the image of a steel plate hundreds of light-years thick.

New avenues were thrown open to the theoreticians by advances in neutron physics resulting from the technological mastering of atomic energy which made possible one of the finest experiments of our age.

A nuclear reactor or pile, whether in a research laboratory, an atomic icebreaker, an atomic power station or a nuclear fuel plant, houses the same fundamental process: fission of nuclei of a radioactive substance by neutrons. In every decay process several nuclei possessing beta radioactivity are formed. If neutrinos exist, the neutrons in these nuclei must decay according to the reaction given above:

$$n \longrightarrow p + e^{-} + \bar{\nu}$$

Suppose we have a 300,000-kilowatt nuclear reactor. The total energy carried away by antineutrinos will amount to tens of thousands of kilowatts. This is very much, but even so it is very hard to catch the ghost particle. Calorimetric effects are useless, for if even half the energy carried by a neutrino stream is to be liberated as heat an absorber with a mass of 10^{60} tons would be required, and this is greater than the mass of the universe by many degrees of magnitude.

But if it is impossible to register the heating of mat-

ter, perhaps it would be feasible to register individual events attributal to antineutrinos?

Theoreticians predicted an interesting nuclear process which could be caused only by a neutrino and antineutrino, if they exist. It is the reverse of beta decay, namely

$$\bar{\nu} + p \rightarrow n + e^{+}$$

All the particles here are known, and one cannot reject the possibility of an antineutrino hitting a hydrogen nucleus. If such a process does in fact take place its probability can be easily calculated. If the experiment registers the same order of magnitudes as yielded by the computations it can be declared successful and the existence of the antineutrino proved.

The best antineutrino source is a nuclear pile, which emits 5×10^{19} of them a second. At a distance of ten metres from the reactor the density of the flux is still 10^{13} antineutrinos per square centimetre per second. Computations indicate that if we bombard a ton of hydrogen-containing matter (which abounds in protons) with such a flux we should register 100 transmutations of protons into neutrons every hour.

The theoretical estimates were brilliantly confirmed, and in 1956 American physicists F. Reines and C. Cowan carried out this exciting experiment.

A neutron flux was directed into a tank of hydrogen-containing substance that scintillated when electrically charged particles passed through it. Every scintillation in the absorber was recorded by a sensitive photoelectric cell.

When an antineutrino collided with a proton the latter turned into a neutron and a positron. The positron produced the scintillation registered by a photoelectric cell. The neutron travelling through the absorber gradually lost speed and, when the speed fell to thermal values, was captured by an atom of the absorber. The capture increased the atom's energy, which released a burst of gamma quanta that were also registered. Thus each interaction of an antineutrino and a proton was accompanied by two flashes of light, the first at once, the second after a certain delay. In an effort not to miss a single scintillation the experimenters used more than a hundred photo multipliers. It was the first time in nuclear research that such a huge absor-

ber was employed. This was necessitated by the antineutrino's passiveness. A smaller scintillator would have produced too few registered events. The experiment, truly unique in the difficulties that had to be overcome, took five years to prepare.

Another problem remaining to be resolved was to prove conclusively that the neutrino and antineutrino are different particles. Bruno Pontecorvo suggested the following ingenious way of doing this.

First of all, what do we call an antineutrino and what a neutrino? So far we have been calling an antineutrino the particle emitted together with an electron in beta decay. Another type of decay is so-called beta-plus decay in which a proton spontaneously transmutes into a neutron, positron and neutrino. The terminological question is not a fortuitous one. Actually, we could switch the particles' names and nothing would change. Furthermore, we would consider the electron positively and the positron negatively charged without altering the world around us at all. The important thing is to have a correct understanding of the essence of the differences; nomenclature is secondary. But to avoid confusion and speak the same language physicists must agree on terms. True, having separated the neutrino from the antineutrino, we have not yet answered the question whether they are identical or different in some physical properties. When, later on, we will say that elementary particles have other types of charges besides electrical the meaning of this question will be finally clear. Meanwhile we shall restrict ourselves to the undeciphered term, "neutrino charge". It was this that had to be determined. Either the neutrino and antineutrino possess opposite "neutrino charge", and then they are truly different particles, or they are genuinely neutral, and in that case they are one and the same particle.

The principle of the experiment is explained by the reactions:

$$\nu + p \longrightarrow n + e^+$$
$$\bar{\nu} + n \longrightarrow p + e^-$$

Both are derived from known reactions by the simple substitution of a neutrino for an antineutrino and vice versa. If the difference between the particles is purely formal the reactions are, obviously, possible. If the neu-

trino is a different particle than the antineutrino, then the reactions are impossible.

Only one of these reactions has to be checked to obtain a unique answer to the question. This is just as well since we have no powerful producers of neutrinos whereas uranium piles produce powerful fluxes of antineutrinos. So all that is left for us to do is to verify the second reaction.

This verification is analogous to Reines and Cowan's experiment, and it was carried out by the American Davis, who studied the interaction of the antineutrinos with chlorine-37 nuclei. He found that the process $\nu + \mathrm{Cl} \rightarrow \mathrm{Ar} + e^-$ does not occur. Hence the neutrino and antineutrino are different particles with different signs of the "neutrino charge". However, the "neutrino charge" is not the only difference between the two.

COSMIC WANDERERS

Ever since the discovery of the positron in 1932, nuclear physics and the physics of elementary particles have been closely connected with cosmic ray research. In search for their quarry hunters for cosmic rays ascend in balloons, climb rocky mountains, descend into ocean deeps and mines and launch balloons and space rockets. This is understandable, for many of the possibilities for experiments presented by nature cannot be achieved even in the best of physical laboratories. Cosmic rays contain particles with energies millions of times greater than can be achieved in modern accelerators. And it is precisely through the world of high energies that the road to the great mystery, that we call "the authentic structure of matter", lies. Without high energies it is impossible to bring particles to within fractions of a fermi (10^{-13} cm) together so as to finally answer the fundamental question of physics: Why are there so many so-called elementary particles?

In the first few years following the discovery of natural radioactivity it was observed that even in the absence of radioactive sources there exists a small but perceptible background ionization. It could be detected by the simplest instrument, an electroscope, the leaves of which collapsed with time because the charge on them was gradually neutralized by some mysterious ionization. Whatever the researchers did to seal the electroscope off and shield it

from radiation and X-rays was in vain and the leaves persisted in collapsing.

At first researchers sought the source of the background ionization in the opposite direction of where it really lay: on, or in, the earth. The verification was simple enough. Obviously, the greater the distance from the source the smaller should the radiation be. So all one had to do was to lift the instrument higher up and see how the background radiation diminished.

In 1909, the Austrian physicist Victor Hess launched a balloon with instruments to measure the radiation intensity at various heights. The balloon reached an altitude of 5,000 metres where, contrary to expectations, the radiation, far from being weaker, proved to be 30 times more intensive than at sea level. At first this discovery of rays reaching earth from outer space caused no great stir in the scientific community, and up until 1932 their study was in no way associated with the fundamental problems of physics. The development of the atomic model, quantum theory and radiation theory pursued their own course, while cosmic rays interested only some meteorologists. More, many scholars questioned the very existence of "cosmic" rays.

It required a second discovery to arouse interest in them. This was to a considerable degree facilitated by the work of L. V. Mysovsky in Leningrad, who studied the intensity of cosmic radiation at various depths in water. Important contributions were made by Bothe and Kolhörster, who designed cosmic ray counters, and D. V. Skobeltsyn, who in 1928 obtained the first cloud-chamber photographs of cosmic rays.

The nature of these rays remained a mystery for some time. Physicists argued fiercely about their origin and many contradictory opinions were voiced. Thus, R. A. Millikan suggested that they represented a flux of gamma quanta or fast electrons. The picture was a vague one, all the more so as it proved impossible even to estimate the energy of primary cosmic rays.

True, the Dutch physicist J. Clay discovered that the intensity of cosmic radiation was affected by the earth's magnetic field, but his data agreed poorly with other observations, many of them fragmentary and contradictory.

The turning point came after cosmic rays unexpectedly

confirmed Dirac's brilliant hypothesis. Arthur Compton organized several expeditions to different parts of the world. Measurements of radiation intensities at various latitudes confirmed Clay's geomagnetic effect. This was of primary importance. If the intensity of cosmic radiation at the equator is 10 per cent lower than at the poles, evidently the magnetic field deflects a portion of the cosmic rays which, obviously, comprises charged particles. The most vivid manifestations of the geomagnetic effect are, of course, the polar lights, due, as is known, to slow electrons. Later the so-called east-west effect was discovered, which is the dependence of the radiation intensity on the orientation of the instrument.

The Englishman Blackett and Italian Occhialini built a cloud chamber controlled by particle counters. It was activated only when real cosmic particles entered, eliminating useless photographs of stray particles entering the chamber. The photograph of the first positron track was made in just such a chamber.

Later Blackett and Occhialini obtained excellent photographs of whole "showers" of electrons and positrons, which proved to be a characteristic feature of the passage of photons and electron-positron pairs through matter. Their work caused a sensation in the scientific community. Here was not just a new phenomenon in the microworld, nor even a prediction of a new particle come true. The main thing was that a scientific abstraction had suddenly been tangibly presented to the scientists' eyes. The ability of gamma rays to produce electrons and positrons, and the latter's ability to annihilate with transmutation into gamma quanta received documentary proof provided by the unbiased testimony of photography. A new fundamental property—the transmutability of particles—entered science once and for all.

But let us return to cosmic rays. Excerpts from their as yet brief history cannot replace a description of their nature and behaviour. This is a chapter which is entering theoretical physics, astrophysics, astronomy and, evidently, in the near future it will also enter applied astronautics. That is why it is of such interest to us.

All cosmic bodies within galaxies—stars, interstellar dust and gas, planets and meteorites—move at comparatively moderate relative velocities not exceeding hundreds of ki-

lometres per second. But the particles of different charge and mass constituting cosmic rays are "relativistic" particles piercing space in all directions at speeds approaching that of light. When physicists speak of the heaviest or slowest particles discovered at the surface of the earth they mean by "slow" those which travel at a mere hundred or two hundred thousand kilometres per second.

Cosmic rays are occupying an increasingly prominent place in science. Not only because they shed light on the world of interactions of high-energy elementary particles as yet inaccessible to us. There is one still poorly investigated, but evidently not fortuitous, point that is arousing interest. The energy density of cosmic rays in interstellar space is estimated to be of approximately the same order of magnitude as the energy density of the magnetic field, to which growing attention is being attached in problems concerning the origin and evolution of galaxies.

Cosmic rays display an extremely broad energy spectrum. One finds particles with energies of 0.2 to 10 GeV and extending well beyond the possibilities of the world's biggest accelerators to fantastic values of 10,000,000,000 GeV which make nuclear scientists' mouths water.

The particles entering the earth's atmosphere collide with the nuclei of atoms of atmospheric gases and become streams of secondary corpuscles. That is why primary cosmic radiation hardly reaches the earth's surface.

The energy spectrum of primary particles is determined according to their deflection in the earth's magnetic field. No particles with energies below 0.2-0.4 GeV have been discovered in primary cosmic rays. This is because the corpuscular streams and magnetic fields spreading out from the sun act like wind that raises light dust and sweeps the low-energy particles outside the bonds of the solar system. The majority of the particles in the rays have energies of up to 10 GeV (the energy of the proton synchrotron at Dubna, USSR); particles with energies exceeding 10^{15} eV are fairly rare.

To capture particles of such tremendous energy the researchers have to build installations with an effective surface of several square kilometres. Even so a particle of 10^{19} eV is detected on average once in 24 hours. Atomic particles of such colossal energy are as it were bridges into the macrocosm, for 10^{19} eV is sufficient energy for

a one-watt bulb to burn for a second and a half, and this is quite a macroscopic effect.

It was most interesting to determine, for purposes of studying the structure of space, if there were any preferred directions followed by cosmic rays. Thus, it had been suggested that the rays may perhaps be restricted mainly to the plane of the Galaxy or the axis of one of its branches in which the solar system lies.

However, cosmic radiation in the Galaxy was found to be isotropic. Precise measurements revealed that the stream of rays reaching the earth is the same from whatever direction they come in.

What then is the origin of cosmic rays? Where are the sources that continuously erupt them into the black void of space? We shall answer these questions later on.

We interrupted our story about nuclear forces because the logic of our narrative required us to make mention of the neutrino, "invented" by Pauli. We led the reader a quarter of a century forward to the time when the existence of the neutrino and antineutrino was proved experimentally. Now we can return to the time when I. E. Tamm enunciated his theory of nuclear exchange forces (taking the neutrino into account). Calculations carried out by Tamm, as well as works by D. D. Ivanenko, A. A. Sokolov, Carl Weizsacker, Wentzel and others showed the impossibility of explaining nuclear exchange forces in terms of the known particles of small mass, the electron and neutrino. The discerning reader will already have guessed that he will shortly meet a new elementary particle. When the physicists saw that some nuclear processes could not be described in terms of known particles, they first "invented" and later discovered a new one.

PARTICLES IN CROSS-SECTION

In 1935, a 28-year-old professor at the university of Osaka, Hidekei Yukawa, advanced the bold idea that nuclear forces are transferred by an unknown particle, which later became known as the meson.

Nuclear forces, which at distances of 2.6 fermis between nucleons are 10 times stronger than electrostatic and 10^{37} times stronger than gravitational forces, dwindle to virtually nothing at only three or four fermis; by comparison,

the radius of action of electromagnetic forces is virtually infinite. With this in mind, Yukawa postulated that the mass of the meson (in Greek "meson" means "in between") must lie somewhere between the masses of the electrons and nucleons. His tentative estimates placed the meson mass at approximately 200 electron masses (e.m.).

As photons interact strongly with electrons, Yukawa assumed by analogy that mesons interact readily with the carriers of the "nuclear charge", nucleons. The new particle's spin was predicted as an integer, making possible an exchange of single quanta.

Yukawa's prediction was confirmed in 1937, when Anderson and Neddermeyer, as well as Street and Stevenson discovered tracks left by some new positively and negatively charged particles on cloud-chamber photographs of cosmic rays.

A somewhat disturbing feature was the discovery of only charged particles and no neutral meson, without which the theory ran into difficulties. A proton could emit only a positive meson, becoming a neutron, and the emitted meson could be absorbed only by a neutron, which immediately transmuted into a proton. Otherwise the proton would turn into a doubly charged particle, which does not exist, and the neutron would become an antiproton (which will be discussed later), which is prohibited by one of the conservation laws. The only exchange between two nucleons feasible is

$$p \longrightarrow n + \text{positive meson and positive meson} + n \longrightarrow p$$

An uncharged meson was essential to explain the charge independence that characterizes nuclear forces and the possibility of exchange between particles of the same charge. Physicists have sought this meson stubbornly. They have even given it a name—neutretto—but so far it has eluded them. (Incidentally, the mesons discovered in cosmic rays were at first called mesotrons, by analogy with electrons. But then it was pointed out that, whereas the name "electron" was derived from the Greek "electra", the Greek word "mesos" has no "tr" in it, and "meson" was accepted.)

Today we know that there were mu-mesons, or muons (μ^+ and μ^-). Muons have a very short mean lifetime, only around 2×10^{-6} second. Their mass is 206 e.m. and their decay formulas are

$$\mu^+ \longrightarrow e^+ + \nu + \tilde{\nu}$$
$$\mu^- \longrightarrow e^- + \nu + \tilde{\nu}$$

Further investigations of muons revealed that they could not be nuclear field quanta. They practically do not interact with nucleons. As the decay schemes show, they obey Fermi-Dirac statistics, and have spins $\frac{1}{2}$. Therefore they cannot be produced one by one and cannot by themselves transfer nuclear interactions.

Illusions, however, die hard, and it was not before 1946 that the impossibility of regarding muons as nuclear field quanta was finally conceded. This happened when the Italian physicists M. Conversi, E. Pancini and O. Picciono discovered the extremely weak interaction of muons with nuclei and the negligible probability of their being absorbed by nucleons.

A way out of the difficulty was shown by the Japanese Sakata and the Americans Bethe and Marshak, who postulated the existence of mesons capable of transferring nuclear forces.

In 1947, Powell, Occhialini and Lattes, working with special thick-emulsion photographic plates, discovered a track of a new cosmic particle which interacted vigorously with nucleons. Thus were the charged nuclear field quanta discovered. They were named pi-mesons, or pions (π^+, π^-). Their mass is 273 electron masses. (For his work in discovering charged pi-mesons C. F. Powell was awarded the Nobel Prize.) Finally, in 1950 the neutral pion (π^0) with mass 264 electron masses was discovered.

The mean lifetime of a charged pion is 2.5×10^{-8} sec; the neutral meson lives only about 10^{-15} sec. Charged pions decay into muons and neutrinos:

$$\pi^+ \longrightarrow \mu^+ + \nu$$
$$\pi^- \longrightarrow \mu^- + \nu$$

The neutral pion transmutes into photons:

$$\pi^0 \longrightarrow 2\gamma$$

These photons may collide with a nucleus and produce an electron-positron pair. It was this reaction which pointed out to researchers the neutral particle π^0 which leaves no track of its own.

Contrary to Yukawa's prediction, the spin of all three types of pion is zero.

Unlike muons, electrons and positrons, pions react extremely vigorously with nucleons, which easily absorb them and in suitable conditions as easily emit them. For that reason nucleons are always surrounded by a pi-meson field, just as a charged particle is surrounded by an electromagnetic field. Pions are capable of sparking strong nuclear interactions in intensity considerably surpassing electromagnetic, gravitational and all other known natural forces.

It is useful to note here that the term "nuclear interactions" we have been using is more often replaced by the term "strong interactions". Besides these, three other types of interactions are distinguished; weak, electromagnetic and gravitational. Physicists define interactions in terms of the so-called coupling constant: $2g^2\pi/hc$.

For strong interactions, associated with the pi-meson field, the constant is the highest, at about 15. Electromagnetic interactions associated with electromagnetic field quanta are much weaker (coupling constant 1/137.03). Weak interactions, associated with electron and neutrino fields and most usually manifest in beta and meson decay, have a coupling constant of only about 10^{-11}. Finally, gravitational interactions, the weakest of all, are characterized by the gravitational "charge" $\sqrt{\chi m}$, where m is the mass of the particle and χ is the gravitational constant. Even for the heaviest known elementary particles the coupling constant for gravitational interactions does not exceed 10^{-48}, which is 37 orders of magnitude weaker than for "weak" interactions!

At present we are concerned with the strong interactions which are responsible for the attraction between nucleons. Thanks to pi-meson exchange the proton and neutron undergo reciprocal transmutations which in effect agree with Tamm's initial scheme, except that the transfer of quality is effected by pions instead of electrons or neutrinos. The distinction, however, is an essential one. The exchange between proton and proton as well as between neutron and neutron is effected by the neutral pion, which explains the charge independence displayed by nuclear forces.

Nucleons emit and absorb pions, but this does not mean that pions are in any way components of protons or neutrons.

The case is similar to that of electrons, which are capable of emitting and absorbing light quanta. This is one of the "strangenesses" of the quantum world we must get used to live with.

The physicists decided to use accelerated electrons or very hard gamma rays to probe the inner structure of nucleons. The very first experiments revealed that the proton's charge density diminishes smoothly to the periphery. The neutron, however, displayed stranger qualities: its electrical radius turned out to be zero, at any rate, many times smaller than the proton's. This indicates that either the neutron is completely neutral or its electric charge is concentrated within a radius tens of times smaller than the proton's. In general, nucleons were found to resemble the planet Saturn. They have a central region or core surrounded by a cloud of pions, or meson shell. If the core is positive and the shell comprises neutral pions, we have a proton. If the shell comprises negative pions, it's a neutron. The core can also be neutral, with a shell of positive or, in the case of the neutron, neutral pions.

The bombardment of nucleons with high-energy particles can produce mesons. This, however, does not mean that the nucleons' shells are stripped off, leaving the core bare. The nucleon actually retains its initial form, being typical of those proverbial animals that can be flayed twice and more without ever exposing the core bare. This does not mean that nucleons have inexhaustible pion reserves. The ability to breed pions doesn't mean that they are contained within nucleons.

One nucleon structure continuously reverts to the other. Protons and neutrons are mixtures of all possible states of each. But the picture of nucleonic cores swathed in meson shells does not agree with data revealing the marked difference between the electrical radii of protons and neutrons. We have mentioned before that the neutral neutron's core can, feasibly, be positively charged.

Soviet scientists D. I. Blokhintsev, V. S. Barashenkov and V. M. Barbashov put forward a theory of electromagnetic nucleon structure that is in complete agreement with experimental data. It assumes the existence of two types of distribution of electromagnetic density: for the nucleon as a whole and separately for its core. The proton is more electropositive than its core which, as stated, can also

be neutral. The neutron's core can, accordingly, also be either neutral or positive (within a shell of negative pions). It follows that there are different regions inside the neutron, some with a positive charge, some with a negative, which cancels out the positive one. Physicists, however, think that this apparent complexity of nucleon structure may hide an essential simplicity. But the simple things have to be discovered through a maze of intricacies, just as the discovery of numerous elementary particles helps elaborate hypotheses concerning their essential unity. Some recent data, it should be said, seems to indicate that the neutron is, after all, wholly neutral.

Experiments with nucleon-nucleon scattering indicate that the core has a radius of about 0.2 fermi. Nucleon cores repulse one another with tremendous force. The nature of the repulsion forces, which are not connected with meson exchange forces, is still not clear. The core contains some 80 per cent of the nucleon's mass, the balance forming the rather loose shell.

It must be said that the problem of particle structure has undergone a curious evolution. In the initial stages of the development of electron theory no one doubted but that the electron possesses certain dimensions and, accordingly, an internal structure. The whole problem seemed to be only of experimentally determining the modes of charge distribution within a specific "classical" radius. Soon, however, it was found that such naive concepts of particle structure clash with the principles of relativity theory. Physicists were compelled to give up the model of the electron as resembling a tiny planet, though some continued to hold that the electron was a point, not something smeared out in space-time.

Today the erroneousness of these views is beyond all doubt. Contemporary physics has many ways and means of studying particle structure.

One method of studying proton structure employed at Dubna is the study of the elasticity of high-energy pion-proton scattering:

$$\pi + p \rightarrow \pi + p$$

The typical case is when a primary pion deflects only slightly from its initial path and the proton recoil is insignificant. Such a process cannot, of course, take place

in a very small space-time cell. Estimates indicate that the dimensions of the pion-proton system in this case are around 10^{-13} cm.

A more detailed picture of elastic pion-nucleon scattering can be envisaged in the following way. Protons absorb pions so vigorously that a proton can be treated as an almost "black" ball in the path of a pion beam. The scattering of pions is a consequence of their diffraction on the "black" ball. By measuring the degree of diffraction we can judge of the dimensions of the ball and the meson absorption coefficient. These experiments have been carried out many times and they indicate that the absorption increases sharply toward the centre of the nucleon and decreases rapidly toward the periphery at, approximately, $r=0.5\times10^{-13}$ cm.

The structure of nucleons can also be determined from their scattering of electrons, a method which makes it possible to establish the charge distribution and existence of electric current within the nuclear particle. Interestingly, the fall-off in charge density commences in the same region where the coefficient of pion absorption drops sharply.

A theoretical calculation of a nucleon's charge density has suggested the existence of the three regions: the core (10^{-14}cm), pion atmosphere (10^{-13}cm), and pion stratosphere ($<10^{-13}$ cm). It is no longer possible to speak simply of a pion shell. The shell has acquired a more refined structure resembling the gas envelope surrounding the earth.

Following the experimental determination of the structure of the neutron and the proton, one could have expected other heavy particles to display a similar structure. Another matter, again, are particles like pions and K mesons, on which experimental data are lacking, though some indirect data do make some surmises concerning their structure possible.

Surprisingly, we know least of all about the structure of the electron, that veteran of the microworld which even the ancient Greeks could produce by the simple expedient of rubbing a piece of amber on sheepskin. Yet to this day we can only hypothesize about the atom of electricity's structure. Nature has been most abundant with paradoxes in the microworld, and as often as not the apparently simplest things turn out to be of bedevilling complexity. Particles are inexhaustible. Often a person thinks that he knows

virtually everything about some particle and all he needs is one more tiny step forward, when all of a sudden a chasm opens up before him. And again he must plunge into the unknown and embark on the construction of more general theories. If one is to believe theoretical electrodynamics (and there is no reason not to, if only because so far it remains the best of all existing field theories), the electron should be a virtual colossus among particles, with a diameter at least 100 times greater (10^{-11} cm) than could be expected on the basis of classical physics. But then, when physicists speak of the electron's diameter they do not mean the diameter of a bead: 10^{-11} cm is the dimension of the space surrounding the electron in which vacuum is polarized. One could say, in other words, that 10^{-11} cm is the size of the atmosphere of electrons and positrons surrounding the electron. Owing to the weakness of electromagnetic interactions this atmosphere is extremely rarified, to use another conventional concept in our analogies. Thus, whereas the pion atmosphere around a nucleon can be compared with the earth's, the electron with its envelope is more like Mars. That is why direct experimental data to support this idea of the electron's structure is lacking, though some extremely delicate shifts of levels within the hydrogen atom seem to favour the "Martian atmosphere" model.

Perhaps new information on electron structure will be forthcoming from experiments employing colliding electron beams.

PSEUDO-ATOMS

Ever since Rutherford carried out his now classical experiments physicists have been doing all they can to break the atomic nucleus. Bombardment of atoms with a host of particles of different kinds has provided insight into the complex structure of nuclei and the laws and forces governing life in the microworld. If not for this driving urge to crack the nucleus man today would have neither nuclear energy nor many of the artificial radioactive isotopes which have become practically household names. Most of the known elementary particles owe their discovery to nuclear bombardment. Bombardment is destruction, but it can also be likened to thorough, painstaking analysis. In science

a period of analysis is always followed by a period of synthesis. And this brings us to the story of the creation of synthetic atoms.

In speaking of the discovery of positrons we noted one interesting circumstance. An electron and positron usually annihilate with the emission of two quanta, much rarer three or one. A little later we shall explain the reason for this. Meanwhile we offer you the first synthetic atom: positronium.

Positronium is formed at the moment when a positron meets an electron before they annihilate. For an infinitesimal fraction of a second the particle and antiparticle form an unstable atomic structure. The two particles start chasing each other around their common centre of mass like two gladiators, each striving to find his adversary's weakest spot and deliver the *coup de grace*. Electrically positronium is similar to the hydrogen atom, in which an electron revolves around a proton. But as the positron weighs the same as the electron such a synthetic atom will be some 1,000 times lighter than hydrogen. Its diameter, though, is double that of the hydrogen atom. The lifetime of positronium is measured in ten-millionths of a second in some cases and in ten-billionths in other. But even in this infinitesimal time our "gladiators" manage to make a million revolutions or so. The chase is deadly to both, and without ever even touching each other, they both annihilate and turn into light quanta.

Why is it that in the annihilation usually two or more photons appear, but not one? This is due to the inexorable law of conservation of momentum. No matter how many bodies take part in an interaction the total momentum must always be the same. To every action there is always an equal reaction.

When we fire a gun, as the bullet flies off we feel the recoil of the butt on our shoulder. When a photon flies off as a result of electron-positron annihilation the inevitable recoil takes place with another photon of equal energy flying off in the opposite direction.

Occasionally positronium leaves three photons behind, and theory provides for the possibility of more quanta being formed. In this case the released energy is distributed evenly between them all. But most frequently positronium decays with the emission of two (para-positronium)

or three (ortho-positronium) photons. The lifetime of para-positronium is 1.25×10^{-10} sec, of ortho-positronium, $1.4 \times \times 10^{-7}$ sec.

To understand why this happens we must go back to the spin concept. The spins of the electron and positron in the positronium pair may be either parallel or antiparallel, hence the combined spin will be either unity or zero, making either ortho-positronium or para-positronium, respectively. At the moment of annihilation there takes place a sequence of subtle and complex interactions which depend completely on the sense of the particles' spins.

The law of conservation of moment of momentum prohibits ortho-positronium, with its unity spin, from decaying into two particles, as the total spin of two photons must be either two or zero. Therefore ortho-positronium can decay only into three photons. Two antiparallel photons yield a total spin of zero, and the third photon accounts for the unity value of the spin of ortho-positronium. It is natural to expect para-positronium, with its zero spin, to decay into two antiparallel photons.

Positronium is not the only variant of a synthetic atom, or perhaps "pseudo-atom", one might say. The quantum field also presumes the possibility of a mesonic atom being formed. This can be envisaged by mentally substituting the electrons spinning around the atomic nucleus with negative mesons. We have already said that to each electron corresponds its definite discrete orbit according to its energy. If the nucleus captures a gamma quantum from outside its energy will increase and an electron will jump to a more distant energy level. Electrostatic forces inevitably return the electron to its own orbit, and the nucleus throws off the recently absorbed energy, again as a gamma quantum. The atom of every element has a specific number of energy orbits, which is why the photons emitted by the nucleus are also characterized by a specific radiation frequency.

If the electron in a hydrogen atom is replaced by a negative meson the latter will also be able to occupy only a certain number of orbits; for a muon the diameter of its permitted orbits will be smaller as many times as it is heavier than the electron, that is, 210. The wavelength of the gamma quanta emitted by the nucleus will decrease by the same factor. The same holds for the case of negative

pions, but here the orbit diameters and radiation wavelength will be smaller by a factor of 273. A result of the reduction in wavelength is that, instead of visible light, the atom begins to emit X-rays with a very low penetrating ability, which makes it hard to detect them. That is why physicists prefer dealing with heavy mesonic atoms with shorter radiation wavelengths.

The differences in the properties of pions, which interact vigorously with nucleons, and the nuclearly inert muons are displayed vividly in the behaviour of mesonic atoms. Owing to the weak interactions of mu-mesons with the nucleus, the muonium usually decays on capture whereas the pionium has a considerable chance of being captured by the nucleus prior to decay. The fact that the mesons in a mesonic atom revolve so close to the nucleus makes them suitable for studying the dimensions and shapes of the nucleus.

The first mesonic atoms were produced in a synchrocyclotron in 1952 (pioniums were discovered by Kamak, and muoniums, by Fitch and Rainwater). Later L. A. Alvarez and his colleagues discovered the possibility of creating muonium molecules.

A beam of negative muons is retarded to thermal velocities, at which they are captured by nuclei, while special counters measure the wavelengths of the X-rays emitted by the excited nuclei of different elements. Relatively light elements, like nitrogen or carbon, radiate at wavelengths corresponding fully to the difference between the muon and electron masses. However, when the experiments were carried out with heavier elements the X-ray radiation energy dropped sharply. What had happened?

Let us consider a model of an atom of lead with 82 electrons revolving about the nucleus. If one electron is replaced by a meson its closest possible orbit will be 82×210 times smaller than the diameter of a hydrogen atom (10^{-8} cm), or 5.8×10^{-13} cm. But the nucleus of an atom of lead is 17×10^{-13} cm in diameter, which means that the muon's orbit must lie well within it! There is nothing incredible in this. Impermeability is a quality that characterizes only the world of big things, the world we live in. In the microworld there is simply no such property, and the muon is quite capable of moving about in such a densely packed body as the atomic nucleus. In fact, within 100-millionths

of a second the muon sails trillions of times around its orbit inside the nucleus before it is absorbed by the nuclear matter.

The pion's behaviour is different. The pion, it will be recalled, reacts vigorously with nucleons, and as soon as it reaches the closest orbit to the nucleus it is captured by a proton. The energy of the captured pion explodes the nucleus with great force, which can be observed by the stars formed in thick photographic emulsion. These photographs are additional reminders to us that elementary particles are in fact not at all so elementary.

NUCLEAR MAGIC

Atomic nuclei, according to American physicist Robert Hofstadter, are hopelessly invisible. One can't help agreeing with this even though one's being rebels against the idea of "hopelessness". It is doubtful that man will ever get a direct look at an atom, at least in the foreseeable future. The scintillations on counter screens, the vapour tracks in a cloud chamber, the dotted lines in thick emulsions are only indirect manifestations of particles and nuclei.

The problem of nuclear structure is closely linked with that of nuclear forces. On several occasions in this book we have attempted to explain these forces, but however ordered the picture may have appeared at first, ultimately it always turned out that some considerations had not been taken into account or some observations contradicted the accepted scheme. Unfortunately, we have no other explanations of nuclear forces than that offered in our description of the pion-quanta of the nuclear field. To date this remains the "last word" in nuclear physics and only the future will yield a new scheme. This is due not so much to the dialectics of absolute and relative truth as to the concrete manifestations of this dialectics. We still lack final information on the nuclear forces acting between two nucleons, and this explains why the distribution of proton and neutron aggregates in the nucleus is poorly known. And who knows what we shall achieve first, a direct glimpse of the nucleus or trustworthy knowledge of the laws governing the coexistence of its inhabitants?

Theoreticians have, naturally, been compelled to resort to approximate models which may well retain their value after the question of nuclear forces is resolved. And if we just spoke very approximately of the structure of nucleons, with atoms the question is much simpler. An atom has a central body in which is concentrated practically the whole of the mass and *the* whole positive charge, and the movement of electrons is governed mainly by Coulomb's law.

Shortly after the composition of the atom's nucleus was established two models of its structure were suggested, the liquid-drop and the shell model.

As mentioned above, nucleons interact only at very small distances, hence, each one interacts only with its closest neighbours. This property of nuclear forces enabled Ya. I. Frenkel, corresponding member of the USSR Academy of Sciences, to liken the nucleus to a drop of liquid in which the particles also interact only with their immediate neighbours. The similarity, however, extends farther. For if nucleons are arranged in the nucleus like molecules in a drop of water then the density of the "drop" must be constant for all nuclei without exception and the "drop" itself must have a clearly defined surface. Like big and small drops of rain, the nuclear "drops" should be of the same density in the case of "big" uranium and "little" hydrogen. Accordingly, their volume must be in proportion to the number of nucleons. And as the volume of a sphere is in proportion to the cube of its radius, the atomic radius must be in proportion to the cube root of the number of nucleons. This makes it possible to measure the nucleus of any atom.

The nuclear charge is also distributed evenly throughout the "drop's" volume. This means that the charge density must differ for different elements, depending on the ratio of protons in the total nucleon count. As the hydrogen nucleus has no neutrons at all, obviously its charge density is the greatest.

To chip a nucleon out of a nucleus requires an energy input equal to the binding energy. Therefore, if we are interested in the reverse problem of getting a nucleon into the nucleus we must expect the nucleus to give off the same quantity of energy. Getting a proton into the nucleus is a hard job as it is necessary to overcome the forces of electrostatic repulsion that develop between charges of the

same sign. This can be achieved by accelerating the proton. Thus, to overcome the repulsion between a proton and a nucleus of heavy hydrogen (deuterium—its charge is unity, as its nucleus comprises a proton and a neutron) a proton has to be accelerated to more than 0.5 MeV.

Forcing a proton into heavier nuclei is even harder, as the required energy increases in proportion to the product of the interacting particles' charges.

Obviously, the neutron, with no electric charge, is much more suitable for nuclear fission reactions.

A neutron entering the nucleus releases about 8 MeV, heating the nucleus, which radiates the excess energy as photons. The photons also carry off part of the mass equal to the quotient of their energy divided by the square of the velocity of light. Hence, the mass of a nucleus that has absorbed a neutron and emitted energy equal to the binding energy is less than the initial total mass of the nucleus and neutron. Similarly, the mass of the nucleus is always less than the total mass of the nucleons it comprises.

This difference is called the mass defect and it is a quality typical of the microworld with no analogues in the habitual phenomena of the world about us. When we see the ram of a pile driver lifted up we know that when it falls it will do work. The higher it is the greater the work it will perform, which is to say: the greater the potential energy of a raised body the greater its kinetic energy of fall. Introducing the mass-energy equivalence, the mass of the ram and the earth, towards which it falls, will be the greater the higher the ram is from the ground. But the gravitational force is too small for such a change of mass to display itself, and there is no instrument capable of detecting the difference in the mass of the two systems: the earth with the ram lying on it and the earth with the ram raised over it—even to the altitude of an artificial earth satellite.

In the microworld, where powerful nuclear forces come into play, the mass defect manifests itself appreciably.

The mass defect is the higher the greater the energy evolved in the production of the nucleus and the closer the nucleons are packed within it. The densest packing is observed in the nuclei of atoms in the centre of the Periodic System, approximately from silicon to tin. This is in com-

plete agreement with the drop model of the nucleus. As is known, a sphere is the most favourable volume; also it is hard to make a true sphere out of a small number of nucleons. The larger their number the more proper the sphere. It follows from this that if we join two light nuclei together, thereby increasing the number of nucleons, we will at the same time achieve denser packing. And what, basically, characterizes packing density? The mean distance between nucleons. This distance is reduced and, accordingly, a quantity of energy is emitted. This is the principle on which the nuclear reactions of synthesis, or fusion, are based.

Of course, for two light nuclei to fuse it is first necessary to overcome the electrostatic repulsion. As we have seen, the repulsion forces are the smaller the smaller the number of protons in the nucleus. That is why the best material for nuclear fusion reactions is the heavy hydrogen isotope, deuterium, and the unstable isotope, tritium.

Deuterium-deuterium and deuterium-tritium fusions yield helium and one free neutron, which enters into further fusion reactions:

$$D^2 + D^2 \longrightarrow He^3 + n^1 + 3.3 \text{ MeV}$$

$$T^3 + D^2 \longrightarrow He^4 + n^1 + 17.6 \text{ MeV}$$

The second reaction, it will be observed, yields much more heat. At present fast fusion reactions have been mastered in hydrogen bomb explosions. A continuous reaction in which the energy could be used has not yet been achieved.

A little earlier we said that the more nucleons we have the easier it is to make a proper sphere. Why then are the median nuclei the more densely packed? It would appear that the heavier nuclei should also be the denser. The explanation is provided by the laws of dialectics so frequently referred to. Once again, quantity develops into quality, this time of an opposite nature, for now the large number of protons mutually repelling each other affect the state of the nucleus. Furthermore, heavy nuclei contain relatively more neutrons, which is why when they decay the nucleons split into two lighter and more densely packed nuclei. Evidently, energy is evolved in the process, a portion of which is used up on imparting kinetic energy to the new nuclei and the balance is radiated off. The median

nuclei contain relatively less neutrons than the heavy nucleus that produced them, thus yielding an excess of neutrons. These "unemployed" neutrons in part fly out of the system and in part emit electrons, transmuting into protons, thus restoring the nucleon equilibrium. Electron emission is not always instantaneous and in some cases it may be a fairly long process passing through several stages. That is why the nuclei formed in the fission reaction are radioactive. Physicists call them radioactive fission fragments.

The drop model offers a good explanation of the fission mechanism. A neutron penetrating the nucleus of a heavy element (uranium-233, uranium-235, or the synthetic plutonium-239) gives off binding energy and heats it. The nucleus begins to boil like a drop of water on a hot frying pan. It pulsates, alternately extending and drawing back into a sphere. As the nucleon attraction forces in a heavy nucleus are weaker than in elements with denser packing the nucleus draws out more and more until the big "drop" breaks into two. The neutrons freed in the process quickly find work in neighbouring nuclei and the reaction gathers momentum like an avalanche. This is how the chain reaction of uranium fission takes place. We have mentioned it only insofar as it can be explained in terms of the drop model.

But there are facts which contradict this model. Nuclei with an even number of protons are more stable than those with an odd number, and "even" nuclei are more abundant in nature than "odd" ones. An even number of neutrons also contributes to nuclear stability. But the most stable nuclei, with the highest binding energy, are those in which the number of protons or neutrons is 2, 8, 14, 20, 28, 50, 82, 126. These numbers are called "magic", perhaps as a tribute to the high stability they impart to the nuclei.

Nuclei with magic numbers absolutely refuse to capture neutrons. If a "magic" nucleus does display alpha radioactivity the energy of the radiated alpha particles is very small. "Magic" nuclei possess other properties indicative of their higher stability. The diversity of nature is great indeed.

The main difficulties facing physicists in their attempts to explain the properties of atomic nuclei are due to the fact that most nuclei are very complex systems comprising many (sometimes more than 250) nucleons. To calculate the properties of such a system it is necessary to solve

a problem of motion involving all the interacting particles. The difficulties will be appreciated if it is noted that the problem for only three nucleons has not yet been solved to a satisfactory degree of accuracy.

Another unknown quantity is nuclear forces, and we still do not know for sure how the nucleons within a nucleus interact.

Working from an analogy with electron levels in the atom, physicists suggest that in the nucleus there are also levels or shells filled with pairs of nucleons (two protons, two neutrons) with antiparallel spins. Nuclei with completely filled shells are the most stable: this is the secret of the "magic" numbers.

The shell model of the nucleus has lately been used to explain a number of very interesting observations. Although it contradicts the drop model, both are confirmed by numerous experimental data. Physicists even find domains where both models are to some degree equally valid.

As long as the nucleus is not excited, not heated, the nucleons in it are arranged, according to the laws of quantum theory, in shells. When a neutron enters the nucleus from outside it heats and boils, the nucleons leave their shells, their movements become chaotic and the nucleus resembles a drop of liquid.

But there are also facts which contradict both models, which means that in future some new theory of nuclear structure will be suggested and it will evidently incorporate all of the best traits of both the shell and the drop models.

The shell model, however, has not yet been exhausted, and theoreticians are thinking of supplementing it to take account of phenomena occurring at the surface of the nucleus. Close to the surface nucleon density and the magnitude of the field in which they move (it is called a self-consistent field and is determined by the aggregate action of all the particles within the nucleus) decrease rapidly. Accordingly, interactions between individual nucleons begin to play an increasingly important part. This should lead to the formation of nucleonic groups at the nuclear surface. Due consideration of surface effects, which, incidentally, have lately been confirmed experimentally, will probably make it possible to considerably expand the applications of the shell model.

It is not so long since a question about the shape of the nucleus would evoke the reply, "Spherical, of course! It's natural!" But it isn't natural—at least in the sense of it being the only possible shape. Actually, we think of atoms, nuclei and even elementary particles as of little beads only by force of habit, repeating a mistake rooted in the darkness of bygone ages. When we finally get a look at the nucleus we may be surprised to find that it is quite unlike any known geometrical figure. In fact it would be natural to expect the microworld to have a geometry all its own. But in the interim, when speaking of the shape of nuclei, we must operate with conventional notions.

Experiments have been performed which indicate that many nuclei are ellipsoids of revolution. This picture has made it possible to explain the energy sequences and differences of weakly excited levels of many nuclei, as well as the high values of the quadrupole moments of their basic states. Quadrupole moment is one of the fundamental characteristics of the nucleus. A quadrupole is a system of charges that create the same kind of field as four charges of equal absolute magnitude, two positive and two negative, located at the corners of a square so that the positive charges are at the ends of one diagonal and the negative are on the other. The quadrupole moment equals the product of the area of the square and the charge. The quadrupole moment of a spherically symmetrically distributed charge is zero.

But before the ellipsoid of revolution shape had had time to gain a foothold, data began to appear which indicated certain deviations. To explain them Soviet physicists Davydov and Filippov suggested that the nucleus is shaped as a triaxial ellipsoid, a model which enables many of the experimentally observed values to be computed theoretically. Moreover, at the time of writing no refutation of this model has been proffered and at worst the experimental data do not contradict the notion that some nuclei may be triaxial ellipsoids.

Nor does this exhaust the diversity of nuclear shapes, and if ellipsoids are related to a sphere (which can be regarded as a special case of an ellipsoid—an equiaxial ellipsoid), a peanut-shaped nucleus is something more outlandish.

Invading the domain of chemistry, we know that the atoms of most elements can join in molecules. The forces that keep atoms together in molecules are explained in terms of quantum mechanics. The main part in molecule formation is played by so-called exchange interactions in which the atoms' valence electrons change places and a common electron cloud appears which holds the atoms together.

A very interesting and very important discovery was made by Canadian physicists Bromley, Almquist and Kuiper. They carried out a number of subtle experiments involving the bombardment of nuclei with such heavy projectiles as oxygen, carbon and nitrogen nuclei and established that, not only atoms, but their nuclei, as well, could join in molecular systems.

In launching their experiments the physicists had not, at first, looked forward to any epoch-making finds. After all, protons, deuterons and alpha particles are themselves nuclei, only light ones. Bombardment with heavier nuclei was no more than a logical continuation of experiments which simply had to be carried out. Many difficulties had to be overcome before the accelerators capable of producing beams of heavy nuclei without admixtures of electrons could be built.

The Canadian physicists employed a five-megavolt electrostatic generator to accelerate carbon and oxygen ions. When a highly accelerated nucleus of carbon-12 collided with a twin nucleus and the radiation curve of the bombarded nucleus was photographed the physicists discovered with amasement that the curve displayed some remarkable characteristics.

Formerly physicists had had to deal only with smoothly ascending curves, and this was easily explained: the intensity of alpha particles emitted by the target nucleus increased together with the energy of the beam of nuclear projectiles. This was because, owing to electrical repulsion, at low energies nuclei do not approach close enough to fuse. But as the energy increases the possibility of fusion also increases, together with the radiation intensity. This was the case when the interactions of oxygen nuclei were studied (O+O).

The curve of the reaction (C+C) proved to be quite different, its smoothness broken by a series of humps.

Imagine a physicist working out the possible mecha-

nism of a (C+C) reaction in advance. Most probably, he would reason, the collision of two C^{12} nuclei will produce a highly excited composite nucleus of magnesium Mg^{24}. In fractions of a second it will decay with the emission of one or several protons or neutrons, in some cases alpha particles, and in all cases gamma quanta. In no case would our hypothetical physicist expect the composite nucleus to emit such a heavy particle as a C^{12} nucleus.

But now he has carried out the experiment, obtained a curve of the (C+C) reaction and proceeds to analyse it. To his amazement he finds, in addition to data confirming the described mechanism, a considerable number of C^{12} nuclei among the reaction products. He is confronted with an apparent contradiction between theoretical notions and experiment. What is to be done?

The contradiction can be overcome by postulating the existence of a "nuclear molecule"—and this is the peanut-shaped nucleus in which the two components do not lose their individuality, do not fuse into a new whole and only adhere to each other, the interaction between them being effected only by the nucleons lying at the interface.

The nuclear molecule is formed from the collision of two carbon nuclei and it exists only for about 10^{-20} sec. The nuclei forming the "molecule" separate again or, in some cases, fuse into a magnesium nucleus.

Unlike the chemical molecule, in the nuclear molecule the nuclei are so close together that the coupling is effected not by electron shells but by nuclear forces.

An ordinary two-atom molecule displays the chemical properties of the respective element. Atomic and molecular oxygen display the same properties in chemical reactions. Not so the nuclear molecule. If one imagines a molecule of two carbon atoms retaining their chemical identity surrounded by the appropriate electron shells it will cease to behave like carbon. Chemically it will be like real magnesium.

But do interactions of heavy ions inevitably produce peanut-shaped nuclei? Numerous experiments with oxygen have revealed that the (O+O) reaction does not produce nuclear molecules. What is the cause of this difference in behaviour?

At present the mechanism that produces the sufficiently long-range attraction forces responsible for the appearance

of nuclear molecules, or quasimolecules, as they are called, is not quite clear. These attraction forces must completely overcome the electrostatic repulsion of identically charged nuclei, which at the distances involved attains very high values. Of considerable importance, apparently, is the deformation suffered by the nuclei in the collision, which may result in a neutron exchange interaction. Oxygen possesses a "magic" nucleus in which the nucleons form closed, saturated shells. As we already know, such a nucleus possesses increased stability, and it is therefore less subject to deformation. So far this is the only explanation of the "normal" behaviour of nuclei in (O+O) reactions.

NUCLEAR MODELS

In the postwar years extensive investigations were carried out of interactions between medium- and low-energy nucleons and nuclei (1-20 MeV). They could be expected with complete probability to display nucleon capture, elastic scattering of incident particles and angular distribution of scattered nucleons. The experimental values of these quantities were found to be in complete agreement with the results deriving from the optical model of the nucleus.

This model pictures interactions between nucleons and the nucleus as passage of the nucleons through a clot of "nuclear" matter. Therefore, the interaction can be characterized in such terms as "optical density", "refraction index" and the distribution of matter within the clot. Experimental verification of the theoretical premises of the optical model revealed, however, that optical parameters were incapable of explaining certain finer details of nuclear reactions. Two opposing tendencies emerged. On the one hand, experiments verified the optical model with more and more precision; on the other, they increasingly revealed its limitations.

The conclusion seems to suggest itself that perhaps all the nuclear models can be brought together into a better, albeit more complex, model. This will probably happen, but it should not be imagined that the new model will represent an arithmetical sum of several components. Simple addition is inapplicable here. Besides, theories usually evolve not only on paper. So, as of today, the best means

of achieving a synthesis of our notions of the nucleus is through experiments.

In 1936 there appeared a classical work by Oge Bohr, *On the Compound Nucleus in Nuclear Reactions.* The essence of this work can be conveyed with the help of certain analogies which, unfortunately, cannot claim either adequate precision or artistic merit. Imagine a three-dimensional billiard table on which the balls can, evidently, move in three dimensions instead of two. A sharply struck ball collides with several others, gradually loses its excess energy and comes to a halt on the table. What has happened to the energy? It has been dissipated amongst the other balls, a little to each, which is why none can receive a sufficient amount to leave the system. Here our analogy ceases. The ball's excess energy is dissipated in collisions, friction, etc. Not in the nucleus.

When, after a number of collisions, a nucleon or alpha particle is trapped in a nucleus the excess energy is not dissipated. In a time fairly great as compared with the characteristic nuclear time of 10^{-21} sec, all or most of the excess energy gathers randomly on a nucleon or group of nucleons (alpha particle, deuteron). The particle that receives the additional energy leaves the nucleus.

The main idea of the mechanism suggested by Oge Bohr is that a fairly long time passes between the nucleon's penetration into the nucleus and the emission of the reaction products. Viewed in slow motion, the reaction can be divided into three stages. The first is when the nucleus captures the incident particle. The second is the relatively long (on the nuclear scale) existence of the compound nucleus in which as yet unknown processes of energy redistribution take place. Finally, the third stage is the emission of a particle from the nucleus which carries off the excess energy.

How long is the "long" existence of the compound nucleus? 10^{-12} second. But this is a thousand million times longer than 10^{-21} sec. The difference between these two numbers is of the same order of magnitude as between a second and a thousand years! One could say that a reaction takes place in the "compound" nucleus every second, but it decays only in a thousand years. A tremendous difference characteristic only of the microworld, which lives according to an entirely different time scale than we are used to dealing with.

Since Oge Bohr suggested his scheme, however, many much faster reactions were discovered. Thus, when a high-energy (30-40 MeV) particle hits a nucleus or even passes nearby it excites motion in the nucleus which takes away a portion of the particle's kinetic energy. The particle flies off without hardly slowing down. The reaction takes place within the time needed for the particle to pass by the nucleus (10^{-21} sec). Another fast process is known as the stripping reaction. When a compound particle flies by a nucleus it can tear one or several nucleons out of it. Theoreticians have suggested several crude models to describe "direct", "non-Bohr" reactions which explain many experimental data.

It might seem that various aspects of nuclear processes are described by numerous, purely speculative, contradictory and extremely restricted models. Such an opinion, however, would mean skimming over the superficial aspects of things.

Currently nuclear physics is witnessing a triumphant synthesis of different models, the erection of bridges between the shell, optical and peanut models of the nucleus. The concepts of compound nucleus, direct processes and optical interactions are being brought together in the theory of nuclear reactions. This is an assault on the greatest mystery of nature launched simultaneously in several places. It is an assault along the whole frontline. It is a broad, comprehensive, long-range quest.

"I see the vast domain of science," wrote Denis Diderot, "as a great field dotted with dark and bright spots. The purpose of our works should be to expand the boundaries of the bright spots or to multiply the sources of light in it. The former is a task for a creative genius, the latter is the work of a penetrating intellect working for improvement."

THROUGH THE LOOKING GLASS

The problem of nuclear forces has led us quite some way. We have investigated the structure of nucleons and nuclei, positronium and mesonic atoms. Now it is time for us to return to elementary particles.

But first an introduction, which at first glance may appear quite unrelated to nuclear physics.

Imagine that one night, when all people are asleep, all the "sides" in our world suddenly change place, left becomes right, and vice versa. Will we notice the change when we wake up in the morning? Before answering this question remember that your right hand is now your left hand, south is north, east is west, and the earth's rotation on its axis and around the sun has reversed. Add such "lesser" details as the change of crystals from right- to left-handed orientation and the changeover of the right and left forms of aminoacids of which proteins are made. Even polarized photons have undergone a change. With all this in mind we can answer the question: and the answer must be negative. We have no way of observing the change and the "new world" will appear unchanged. That this is so is illustrated by a humorous problem suggested by Ya. A. Smorodinsky, which he calls the "Two Picture Houses" problem.

Two identical houses are drawn on the floor in adjacent rooms. All their sides and corners are equal and even the number of curls of smoke rising from their chimneys is the same. There is only one difference: if we could superimpose one house on the other, for the drawings to coincide one would have to be picked up and turned over. But the houses are drawn on the floor and they can't be moved. How is one to discover the only difference between them? Simple enough: go up to one house and see that the door is on the right while the other house's door is on the left. Now suppose we are unable to compare both houses with our non-symmetrical body; suppose, furthermore, that in the other room is a man from the hypothetical "looking-glass" world resulting from the metamorphosis described above, and that our only means of communication is by telephone. We will find some difficulty in trying to explain on what side of our house the door is. And if the man's whole world is a mirror image of ours it will be simply impossible to work things out with him. More, it is impossible to think of a question to ask him to determine whether he is a mirror antipode or a normal man. It can't be done by telephone. The only way is to meet and compare ourselves or to send him some unsymmetrical object, indicating on it what we consider to be the left-hand and right-hand.

All processes in the mirror-reversed world take place just as they do in our own and its inhabitants have no cau-

se to think that they are living in a "reversed" world.

This at first glance rather unserious discourse leads us to an understanding of a very important quality of our world, namely its symmetry with respect to its mirror reflection. It can be defined as follows: No physical phenomenon will change if the "left" and "right" directions are interchanged and the directions of all rotations, including the directions of screws and helices, are reversed.

To compare the conventional world with a physical looking-glass world one must travel from one system to the other with information about the directions in one of the systems. Actually this "someone" must do the impossible. If mirror worlds (with respect to us) do exist they must lie at colossal, insurmountable distances.

We have ascribed our world the property of mirror symmetry. But perhaps on closer inspection we could discover some phenomena contradicting this property? To be sure, the vast majority of people and animals have their hearts on the left side of the body. Most helical shells are curled in the same direction, and even paired pine-tree needles have the same helical twist. Bacteria distinguish molecules of different helicity. Essentially, it is impossible to speak of right-left symmetry in living creatures, and the whole organic world is asymmetrical.

It is interesting that biochemically and biologically right-handed and left-handed compounds are not identical or interchangeable. If, for example, a right-handed amino-acid form in a penicillin molecule is replaced by a left-handed one the preparation will be quite unsuitable as a cure against bacteria. Other such examples could be cited.

There is a very simple way of comparing a normal and mirror world by seeing if a right-handed screw of one will fit into a right-handed nut of the other (the thread is, of course, described from the point of view of the world in which it was made). Continuing the analogy, we can say that, just as it is impossible to fit a left-handed screw into a right-handed nut, so it is impossible to cause effects typical of ordinary organic substances with oppositely twisted ones. Therefore, without, for the meantime, touching on the symmetry law just mentioned, we can say that living protoplasm is asymmetrical. It forms, accumulates and reproduces itself only out of one antipode of asymmetrical molecules. Just as the physicists assume the possibility

of existence of antiworlds made up of antiparticles, so biologists consider possible the existence of a mirror-opposite protoplasm made up not of right-handed carbohydrates and left-handed aminoacids, but of left-handed carbohydrates and right-handed aminoacids.

How did this division of living nature occur? Van't Hoff's theory that the asymmetry of protoplasm developed as a result of the action of circularly polarized celestial light formed in the reflection of the plane-polarized portion of the celestial light reflected from the surface of the seas and oceans can hardly be accepted. Asymmetry is a phenomenon of a much wider and general order. We find asymmetrical molecules everywhere, including places which could never have been reached by light reflected from the ocean surface. Also unacceptable is another "hypothesis" whose author, Jepp, declared in 1898 that asymmetry of protoplasm could be due "only to the effect of the life force".

Of greatest interest to us are statements by Louis Pasteur and V. I. Vernadsky which remarkably echo modern physical conceptions of the world and antiworld.

Pasteur wrote in 1864 that asymmetry of protoplasm is connected with the properties of physical cosmic space. V. I. Vernadsky, familiar with more recent ideas, declared that right- and left-handedness is a property of space and time. He emphasized that it manifests itself in the twist of spiral galaxies and pointed out the need of counting the number of right- and left-handed galaxies in connection with our notions of the structure of space.

All this is sufficient to speak of the existence of mirror symmetry only for phenomena in inorganic systems. As for biological systems, the asymmetry displayed by them could have appeared only from the asymmetry already existing at the time of the origin of life. But much too little is known of the conditions in which living creatures originated and, besides, they are not the subject of this narrative. In future we shall speak only of the inorganic world, in which everything appears to be so symmetrical that not only are the laws of the right- and left-handed worlds identical, but right and left are equally frequent in our environment.

In 1936, the German physicist Kuhn showed that the laws of thermodynamics require the parity of left- and

right-handed forms of crystals and molecules in the inorganic world. Soviet scientists G. G. Lemlein and I. I. Shafranovsky and German scientist Tromsdorf decided to check this proposition by counting many thousands of right- and left-handed crystals of quartz taken from deposits all over the world. The theory was brilliantly confirmed: in all cases the number of right- and left-handed crystals was approximately the same.

Thus, the symmetry of the inorganic world appeared to be something self-evident and, on the whole, not so interesting. All the more surprising was it for the physicists to discover that in the microworld there are phenomena in which the parity of right and left breaks down.

So as not to increase the number of analogies, imagine that on the wonderful night when our world turned magically into its mirror image another equally important event took place. Suppose that the signs of all charges had suddenly been reversed. Positive charges became negative, negative became positive. What happens in this case? Why, the same as in the first—nothing. Physical phenomena suffer no change. A world with negatively charged protons and positively charged electrons would be identical to ours.

In this case, as in the case when the signs of the spatial coordinates are reversed (mirror reflection), something has to be transferred from one world to the other to detect the difference between them.

The symmetry of the world with respect to charge conjugation was discovered not so long ago. Up to 1932 the physicists thought the world to be sharply asymmetrical. This because matter was thought to be made up of light negative electrons and heavy positive protons. But then Dirac introduced into theoretical physics the concept of the positron as a mirror twin of the electron.

It was in his 1933 Nobel speech that he first advanced the idea of antiworlds which is so much in vogue today. If, he said, we accepted the point of view of complete symmetry between positive and negative charges insofar as this applies to the fundamental laws of nature, we would have to regard as accidental the excess of negative electrons and positive protons on earth (and, apparently, in the whole solar system). It was feasible, he said, that there are stars made up mainly of positrons and negative protons, and perhaps there is an equal number of stars of either type.

Their spectra would be identical and there would be no means of distinguishing them by contemporary astronomical methods.

The existence of the symmetry of particles and antiparticles was predicted by a theory born out of the union of relativity theory and quantum mechanics.

The laws of relativity theory are universal and all other theories must obey them. In particular, quantum mechanics must satisfy the following requirement: if an experimenter carries out the same measurements in different frames of reference the results must be identical. This requirement of invariance imposed on quantum mechanics by relativity theory could not be met without antiparticles. It is understandable, therefore, that the physicists were the least surprised by the discovery of antiparticles, for without them the theory would have collapsed.

For many years the electron and positron remained the only example of a particle-antiparticle pair. Yet the existence of a negative proton—an antiproton—seemed only natural as the proton is exactly described by Dirac's equation. But the proton is so much heavier than the electron that the production of a proton-antiproton pair requires an energy input of several thousand million electron volts. But as we have seen, particles of much greater energy have been detected in cosmic rays.

The galactic wanderers had presented physicists not only with the positron but with muons and pions as well. But still the antiproton remained undiscovered. Some people began suggesting that the proton was "not quite" a Dirac particle since, because of its internal complexity (mentioned above), its magnetic moment is almost three times greater than follows from Dirac's equation.

The situation that developed in physics in this connection was characterized by Academician Ya. B. Zeldovich as follows: "The time interval between the prediction of the antiproton and its observation in 1955 was so great that some theoreticians began trying to build up a theory without the antiproton."

The window into the antiworld thrown open by Dirac proved to be a narrow slot. The antiproton failed to appear in cosmic rays, and accelerators at the time lacked the energy potentialities needed to produce it.

Today, with the antiproton discovered and studied, we can explain why it took so long to discover it. The thing is that even given high energies the probability of creating an antiproton is very small indeed, tens of times smaller than, for instance, the creation of a meson. And when an antiproton *is* produced its chances of "survival", that is, of lasting a sufficiently long time to be detected, are also very small as it is absorbed by the nucleus and annihilated.

Thus, the probability of discovering antiprotons in cosmic rays was negligible while accelerators were incapable of passing the threshold of antiproton production owing to insufficient energy output.

All hopes were pinned on the biggest accelerator then in existence, called a bevatron. Would it prove sufficiently powerful to wrench a negatively charged particle of mass equal to the proton out of the antiworld? Most physicists were confident that it would. Both the high standards of the new accelerator and the names of the researchers who were embarking on the quest of the antiproton—Emilio Segré and Owen Chamberlain—favoured the undertaking. In October 1955 the two men's efforts were crowned by success: they produced an antiproton and observed its annihilation.

"Annihilate", of course, means to blot out of existence, to reduce to nothing. In physics the term denotes the transmutation of elementary particles possessing mass into other forms of matter, including matter possessing zero rest mass (gamma quanta). No violation of the law of conservation of matter takes place; only the form of existence of matter changes, the total values of momentum, spin and charge of the system of particles remaining the same as before annihilation.

Foreign philosophical and physical literature frequently employs incorrect terms, such as "annihilation of matter" and "materialization of energy". These terms can give rise to notions that particles of matter can be reduced to nothing or that matter can be created out of "pure" motion. Such conclusions stem from an incorrect definition of matter. Some philosophers and physicists regard as matter only those of its forms which are characterized by rest mass; in this case photons and neutrinos are not "matter".

Operating with such terms as "annihilation of matter", "materialization of energy", "transformation of matter into radiant energy", etc., idealists claim that contemporary physics has proved that matter can disappear and, hence, has refuted materialism. In reality the new discoveries of physics have served to re-emphasize how right Lenin was when he pointed out that expressions such as "matter disappears", "matter is reduced to electricity", etc. are no more than epistemologically helpless reactions to the discovery of new forms of matter and material motion and the realization that the old forms can be reduced to the new ones.

The latest advances of physics in the discovery of new elementary particles and new forms of motion (nuclear processes, annihilation) have served to reaffirm the basic materialist premises. More, the phenomenon of annihilation, which involves reciprocal transmutations of elementary particles, shows that there can be no absolute distinction between various forms of matter, as claimed by metaphysicists. On the contrary, in certain conditions one form of existence of matter can turn into another.

What is annihilation?

We have already spoken of the annihilation of the electron-positron pair. Let us now investigate the behaviour of a proton and antiproton. When they come into contact their total mass degenerates into a shower of quanta. Pions, scattering in all directions at velocities approaching that of light, carry off the released energy, undergo a series of transmutations and trigger various reactions the upshot of which is that the mass and energy of the colliding particles are shared between pions, muons, photons and neutrinos.

It follows that the collision of an atom and anti-atom should give rise to explosive reactions of annihilation involving both the electron-positron shells and the nucleons and antinucleons, and releasing a stupendous amount of energy.

So far science lacks sufficient data which would make it possible to judge of the effectiveness of utilizing annihilation energy. A substantial share of this energy is carried off by neutrino beams and very shortwave gamma rays, which hardly interact with matter. That is why today man is still unable to make use of annihilation energy; if he will one day learn to use it he will obtain a truly inexhaust-

ible source of energy. Just consider: total interaction of matter with antimatter can release 3,000 million times more energy than the combustion of the same quantity of hard coal, 1,000 times more than the "burning" of the same amount of uranium in a nuclear pile, and 133 times more than in thermonuclear synthesis.

So far we have been discussing the antipodes of **charged** particles, the electron and proton. But **neutral** particles can also have antipodes that differ in the direction of spin and, hence, magnetic moment. One pair of neutral particles (the neutrino-antineutrino) has already been mentioned.

The discovery of antineutrons was an inevitable upshot of the experiments of Segrè and Chamberlain, the antiproton pointing out a short cut for it from the antiworld to the physicists' laboratories. Of course, it wasn't all that easy as it sounds, and the physicists had some trouble before they achieved the "nucleon recharging", as they would have called it, in which a proton-antiproton transmuted into a neutron-antineutron pair:

$$p + \bar{p} \longrightarrow n + \bar{n}$$

When a fast proton enters the nucleus it undergoes a rapid transmutation and emerges as a neutron. This was known for quite some time, and the antiproton was expected to display similar behaviour. In fact, following the creation of an antiproton one scintillation counter recorded a flash much weaker than it should have been if it were produced by the antiproton. This meant that some unknown neutral particle had entered the counter. An antineutron? A glance at the next counter revealed that the particle had disappeared in a burst. This meant annihilation: an antineutron colliding with a neutron and carried off in a meson vortex. This very delicate and beautiful experiment which proved the existence of the antineutron was carried out by Cork, Lambertson, Picciono and Wentzel.

In studying the antiprotons and antineutrons physicists discovered an interesting fact: the probability of antiprotons taking part in nuclear reactions was much greater than for protons and neutrons. Perhaps antiparticles are more active? Nucleons have a complex structure which is poorly studied. We can picture them as impermeable cores surrounded by a cloud of pions. But for antiparticles nuclei are not only permeable but also attractive targets.

The strong interactions between nucleons and antinucleons suggest an interesting idea: if a nucleon and antinucleon annihilate into pions, the reverse process should also exist. This means that by retarding a very high-energy pion, a nucleon-antinucleon pair can be created on another pion. The colliding mesons possess a tremendous field of force, and the created pair can be regarded as a quantum of this field. From this follows the legitimate conclusion that not only can a pion be regarded as a quantum of nucleon interaction, but a nucleon-antinucleon pair can with full justification be treated as a quantum of meson interaction. This is an example of the remarkable—and very poorly studied—interactions existing between elementary particles. It enables us to introduce certain corrective factors into the familiar scheme of nucleon structure. We can now regard a nucleon core as the zone of a field the quantum of which is a nucleon-antinucleon pair. True, this concept harbours a certain contradiction, for it works out that the mass of the core of a nucleon-antinucleon quantum is less than the total mass of the individual particles. But in the interaction that breeds the pair the mass increment can derive from the moving mass of the particles, hence the contradiction is only one of appearances. The important thing is that "ordinary" particles contain all the necessary ingredients needed to produce antiparticles.

A remarkable manifestation of the great unity of the material world!

There are no ultimate frontiers of human knowledge. They recede before science just as the horizon recedes before a traveller, and where today the end of the bridge seems to come in sight tomorrow another span is revealed. We will continue our journey through jungles where even theoreticians sometimes feel baffled. We have a moral right to do this, won for us by generations of eminent and unknown contributors to the literary form known as popular science. To be completely frank, there is no great merit in this. A scientist must display a greater or lesser degree of courage to voice a bold guess or light up the darkness of questions on which there exists no consensus of opinion or inadequate experimental data with a flash of inspiration. The popularizer of science simply recounts the ideas of other people. No courage is required here—except if this recapitulation clashes with the views of a reviewer who will vent

his anger on the innocent author. But a degree of risk is inherent in all human activity.

TWO PAIRS OF GHOSTS

We have just seen that antiparticles can be produced by "normal" particles. At the same time we must acknowledge that the nucleon-antinucleon field of a particle core differs in some ways from the corresponding antiparticle field. The cores of two nucleons repulse each other; in a nucleon and antinucleon they annihilate. How does one explain this? As yet there is no definite answer to the question. It can only be conjectured that nucleon and antinucleon cores are made of the same matter in different states.

As our story of the remarkable history of elementary particles advances they appear more and more complex and less and less "elementary". Add to this involved transmutations and intricate decay and interaction schemes, and the picture is one of utter confusion abounding in riddles. In the circumstances it is only natural to seek to classify the particles that have been mentioned here in some semblance of order before continuing on our journey through the microworld which, be it known in advance, will yield more particles and require a revision of the scheme evolved here.

The first obvious thing is that the whole population of the microworld can be divided into particles and antiparticles. Both charged and neutral particles have their antipodes. Even the photon has, in the mathematical sense, an antiparticle. Though in this case the two solutions of the relevant equation can be interpreted in exactly the same way, as the photon and antiphoton are quite indistinguishable. To put it differently, the photon is its own antiparticle.

Thus we have undertaken the first differentiation, the first step in the classification of the inhabitants of the microworld. As yet it does not characterize particles according to their internal properties. Our next step depends on what we call a "particle". After all, we could call the antiproton a "particle" and the proton its "antiparticle". Only the proton was discovered before the antiproton, and we live in a world of protons, which is why it seems only natural to regard it as the "particle". With mesons, however, it is not all that simple. Should we regard the positive or

negative meson as the particle—or antiparticle? It is the same as asking where the moon is, above or below.

So what classification is capable of revealing the inner laws of the microworld?

In the latter forties American physicists Murray Gell-Mann and E. P. Rosenbaum enunciated what at the time seemed to be sound, unshakable theory of the "twelve-particle" structure of matter. These particles included, firstly, such veterans of the microworld as the photon, electron, proton and neutron. Gell-Mann and Rosenbaum introduced such concepts as rest mass (the photon has none), electric charge, which the photon and neutron lack, and the classification of particles according to spin. As we already know particles with spin $\frac{1}{2}$ (electrons, protons, neutrons) are classified as fermions, those with integral spins (photons, pions) are bosons. The twelve particles were later supplemented by the newly discovered antiparticles. According to their rest mass the particles were classified in four subgroups: heavy baryons (protons, neutrons and their antiparticles); medium—mesons; light—leptons (electrons, neutrinos and their antiparticles); and lastly, photons. The theory is sufficiently accurate to explain the properties of atoms. But it proved highly inadequate when it was invoked to help explain internal nuclear processes, though it did offer some generalizations.

The discovery of new particles forced the introduction of additional classifications and showed that the theory failed to reveal the inner laws of the microworld. Particle transmutations, various reversible processes and interchanges—all this bespoke of an essential unity of the microworld. The idea of such unity literally filled the air. But it eluded discovery. The more new particles there appeared in the tables of the microworld the more the physicists wished to reduce them to some minimum of fundamental, primary particles. That is why the discovery of new particles went side by side with the reverse process of their theoretical reduction. Physics aspired toward a unified theory.

The information at the physicists' disposal at the time of the "twelve particles" was on the whole so inadequate that even logically immaculate reasoning could lead to erroneous conclusions. It would be hard to find a better illustration of this than the existence of the muon.

In one of their papers the creators of the twelve-particle theory characterized the muon as a disreputable creation of nature, a particle which had no right to exist from the point of view of theoretical physics and had no reasonable applications. The muon, they declared, was a foundling at the doorstep.

It was discovered before the pion, and physicists at first took it for the nuclear field quantum they had been hunting for. But why is the muon so "disreputable"?

As we already know, muons are produced by pions:

$$\pi^+ \rightarrow \mu^+ + \nu$$
$$\pi^- \rightarrow \mu^- + \bar{\nu}$$

These decay processes are extremely fast. A pion at rest (at rest, because a fast moving one will live longer, in accordance with the celebrated effect of relativity theory) has a mean lifetime of 2×10^{-8} sec.

It would appear that the neutral pion should also decay into a neutral muon ($\pi^0 \rightarrow \mu^0$) but, as shown above, it actually produces two photons. Evidently the absence of a "suitable" neutrino prevents a neutral muon from being produced. But as the neutrino and antineutrino are different particles, $\pi^0 \rightarrow \mu^0$ decay would require the postulation of a "truly neutral" neutrino, a particle which, like the photon, would be identical with its antiparticle. But the neutral muon was not discovered, and today the academicians have accepted the fact that there is a trio of pions but only a pair of muons. Why is this so? Nature remains silent on this score. The muon's existence in no way derives from the twelve-particle theory, although there are reactions in which the muon displays links with other particles. That is why the muon was the first witness to proclaim loudly that the theory was inadequate and perhaps even wrong. Nevertheless, it is interesting to try and fit the muon into the scheme. On the one hand, all processes involving the neutrino (beta decay, pion and muon decay) are characterized by approximately equal coupling constants and are approximately equally weak. Hence, we can state that the muon participates in weak interactions. On the other hand, the muon has an electric charge and, naturally, takes part in electromagnetic interactions. As the muon is a light fermion, it appears reasonable to group it together with the electron and neutrino. Everything seems fine, all leptons are found

in pairs: μ^+ and μ^-; e^+ and e^-; ν and $\bar{\nu}$, etc. But when we turn to the muon's mean lifetime our reasonable proposition begins to appear not so reasonable as the decays we had regarded as equally weak display different lifetimes.

A resting muon decays on average in 2×10^{-6} sec. Its decay scheme is peculiar, and it produces three particles, an electron, neutrino and antineutrino:

$$\mu^+ \longrightarrow e^+ + \nu + \bar{\nu}$$

$$\mu^- \longrightarrow e^- + \nu + \bar{\nu}$$

So far no other processes yielding a neutrino pair are known. Perhaps this is a peculiar property of the muon.

At first it had seemed that the muon could also decay according to the schemes

$$\mu^+ \longrightarrow e^+ + e^- + e^+$$

$$\mu^- \longrightarrow e^+ + e^- + e^-$$

but they have never been observed.

The muon could also have been expected to decay into an electron and a photon:

$$\mu^+ \longrightarrow e^+ + \gamma$$

$$\mu^- \longrightarrow e^- + \gamma$$

but for some unknown reason this scheme was never observed either.

On the other hand, the more complex scheme

$$\mu^+ \longrightarrow e^+ + \nu + \bar{\nu} + \gamma$$

though rarely, is observed.

The riddles emerged as soon as the physicists, excited by the newly discovered pions, turned back to the muon. Solving the riddles is not so easy. An ingenious method was suggested by Bruno Pontecorvo, who followed the example of Wolfgang Pauli and began with inventing a new particle.

To prohibit the decay schemes presented above it is sufficient to assume two types of neutrinos, one produced in muon decay, the other in beta decay. An electron emitted in a decay process is accompanied by a special "electron neutrino" (ν_e), a muon, by a "muon neutrino" (ν_μ). Now muon decay can be written down as follows:

$$\mu^+ \longrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

$$\mu^- \longrightarrow e^- + \bar{\nu}_e + \bar{\nu}_\mu$$

In this case decay without neutrinos is impossible as it is assumed that the two types are so different that they cannot annihilate. The existence of the decay scheme

$$\mu^+ \rightarrow e^+ + \gamma$$

would mean that $\bar{\nu}_\mu$ and ν_e can transmute, contrary to our assumption, into a photon.

Every hypothesis requires verification. The proof of this one would have been the comparison of two beams of antineutrinos, "muon" and "electron" ones (from a reactor). The first should not cause protons to transmute into neutrons, the second should. So thought the theoreticians.

When Pauli postulated that the neutrino should lack almost all the properties of particles of matter he thereby endowed the elusive particle with the unique property of penetrating through vast bodies. This property pointed to the way to produce a pure neutrino beam, making it possible to record the interaction of an antineutrino with matter close to the reactor.

The advantage of a large accelerator over a reactor is that it can produce more kinds of neutrinos: besides the antineutrino emitted in beta decay it is also possible to obtain pion-decay neutrinos and antineutrinos. Bruno Pontecorvo in the USSR and Melvin Schwartz in the USA independently put forward the feasibility of using big accelerators to observe interactions of neutrinos with matter as had been done with a reactor. These experiments were carried out at Geneva and then at Brookhaven. The results surpassed the greatest expectations.

When a neutrino or antineutrino collides with a hydrogen nucleus we can look forward to different consequences. The neutrino should be absorbed by the nucleus, which emits either an electron or a negative muon. What was observed at Brookhaven?

The decay of a positive pion produced a positive muon and a neutrino, which on entering a nucleus "kicked out" a negative muon. If only muons are observed the process can thus be reduced to the creation of oppositely charged muons. A similar result could be expected if pions are simply absorbed by nuclei.

The other possible variant of the process, in which a nucleus absorbing a neutrino could have been expected to emit an electron, did not materialize. An electron is not a repli-

ca of a negative muon, and the two particles are even more different than had originally been thought, it is not restricted to the difference in mass.

The negative muon and electron are interchangeable in all known reactions but they are far from identical twins. Interchangeable in actual fact are the following pairs of particles: the electron with its 'electron neutrino' and the muon with its 'muon neutrino'. In the words of Professor Smorodinsky, "every lepton has its shadow, weightless and invisible, yet different".

Thus, we find that there are not two, but four neutrinos. Both the muon neutrino and the electron neutrino possess left-handed helicity, which is to say that their symmetry is like the symmetry of a left-handed screw and they "corkscrew" into space counterclockwise. The helicity of the corresponding antiparticles is, naturally, right-handed. But the "invention" of new neutrinos failed to strip the dark mask of enigma from the muon. Not least among its puzzling properties is its remarkable similarity with the electron. In fact, the muon resembles the electron so much that it has even been suggested that it is some peculiar excited form of electron. Only why is it 200 times heavier? The similarity may be remarkable, but the difference is no less so.

Nor is the role ascribed by nature to this short-lived weakly interacting particle apparent; actually it seems to be no more than an intermediate link, a brief breathing space in the scheme of pion decay:

$$\pi^+ \longrightarrow \mu^+ + \nu_\mu \longrightarrow e^+ + \nu_\mu + \nu_e + \bar{\nu}_\mu$$

$$\pi^- \longrightarrow \mu^- + \bar{\nu}_\mu \longrightarrow e^- + \bar{\nu}_\mu + \bar{\nu}_e + \nu_\mu$$

So either nature has some use for the muon as an essential link in some unknown processes, or it is useless ask nature all the whys and wherefores, just as it is useless to ask why nature exists at all.

CURIOUSER AND CURIOUSER

The discovery of the muon marked the end of the age of "tame" particles. Like Alice's experiences, the tracks left by weird inhabitants of the microworld in bubble and cloud chambers became curiouser and curiouser. New particles often displayed unpredictable properties which refused to

fit into existing theories. In 1947, C. C. Butler in cooperation with G. D. Rochester (Blackett's laboratory at Manchester) discovered tracks left by unknown transmutation events in cosmic rays. The photographs resembled the Greek letter Λ.

The letter's legs were the tracks of unknown and inexplicable decay processes. The apparent conclusion was that some unknown particle that doesn't leave tracks in the cloud chamber, and is therefore neutral, decays into two charged particles.

Then, as investigation of the mysterious tracks progressed, it became apparent that at least two neutral particles take part in the event. Two new particles at once, and without any theoretical forewarning! No one had predicted them and, in fact, the accepted classification had no place for them!

When passions cooled down a bit the physicists tried, after all, to fit the new particles into the scheme. According to the decay pattern of one of them (into a fermion and boson) the lambda particle (as the newcomer, which decays into a proton and negative pion, was called) had to be a fermion. Furthermore, as one of the decay products was a nucleon, the laws of conservation, which will be discussed later on, required that another nucleon should also take part in the process. For example, a lambda particle can appear in the collision of a proton with a negative pion. The excess energy then must be carried away by some other newly formed particles, a neutral pion, for example. The frequency of the lambda particle's occurrence indicates that it is born in strong interactions. And when its mass was measured it proved also remarkable: 2,182 electron masses, more than a nucleon!

The other particle, which was called a K particle, decays into a positive and a negative pion, and is thus a boson. Its spin, consequently, had to be integral. The physicists immediately favoured a zero spin. As no nucleons were observed in the decay products the K particle could not have been produced as a result of nucleon interaction. It appears as a result of a strong interaction and "weighs" 965 electron masses.

And this is just about all the physicists learned about the two particles at the time. To be sure, the data was sufficient to suggest a classification of the unexpected newcomers. The lambda particle could be classified as a heavy

nucleon—its mass is about the same, it is a fermion and it can be bred by a nucleon. The K particle, a boson, was, in spite of a threefold difference in mass, classified with pions in the meson group.

But this was only the beginning. The physicists had hardly completed their classification of the new particles when a photograph recorded an event in which the Λ pattern was produced by the tracks of an unknown charged particle and its decay products. One of the secondary particles was neutral and, hence, invisible. Then it was found that the K particle could decay varyingly into two or three particles. Discoveries followed one another in rapid succession. There seemed to be dozens of new particles! Before, theoreticians had sought to extricate physics from its difficulties by "inventing" new particles which the experimenters took years to discover. Now the situation had reversed, and the theoreticians were unable to cope with the deluge of new particles produced by the experimenters.

When the spate of discoveries petered out attempts were made to establish order among the crowd of sudden newcomers. They proved not as numerous as had seemed at first.

Today we know that the mysterious particles include heavy ones with masses greater than nucleons (they were called hyperons) and a new kind of meson, the K meson. These can be positively charged or neutral, hence anti-Ks are either negative or also neutral. In this respect they are more like electrons and neutrinos (particles e^- and ν; antiparticles e^+ and $\bar{\nu}$)than pions, but their spin is zero, as with pions.

Hyperons are representatives of an unusual family. They fall clearly into two groups, one comprising the neutral lambda hyperon (Λ^0) and three sigma hyperons, positive, negative, and neutral (Σ^+ with mass 2,327 e.m., Σ^- with mass 2,340 e.m., and Σ^0 with mass of the same order).

The difference between the masses of a hyperon and nucleon exceeds the mass of a pion and therefore these strange particles display a new, fourth type of radioactivity, pion radioactivity. Pion radioactivity was first predicted by V. I. Goldansky, a corresponding member of the Soviet Academy of Sciences. The hyperon antiparticles are also rather unusual. The antilambda is neutral, two antisigmas are charged (the antisigma-minus positively, the antisigma-plus negatively), and the third is neutral.

The other hyperon group displays more similarities with nucleons. It includes the xi-hyperons with mass 2,580 e.m. There are negatively charged xi-plus and neutral xi-zero hyperons with their corresponding antiparticles (the positively charged antixi-minus and the antixi-zero).

All twelve hyperons have spins $\frac{1}{2}$.

Thus, with the four K mesons, a total of 16 new particles were discovered, represented by their symbols as follows:

$$\Lambda^0,\ \overline{\Lambda}{}^0;\ \Sigma^+,\ \Sigma^-,\ \Sigma^0 \text{ and } \overline{\Sigma}{}^+,\ \overline{\Sigma}{}^-,\ \overline{\Sigma}{}^0;$$

$$\Xi^+,\ \Xi^-,\ \Xi^0 \text{ and } \overline{\Xi}{}^0;\ K^+,\ K^-,\ K^0 \text{ and } \overline{K^0}$$

Do not imagine that all the particles were discovered at the same time, as though they had tumbled out of a cornucopia. Much labour, clever experimenting and painstaking analyses went into the work. Suffice it to say that the first particles were discovered, as mentioned before, in 1947, while the antisigma hyperon had to wait 13 years, and the antisigma-zero hyperon is still undiscovered. The antisigma-minus hyperon was discovered in March 1960 at Dubna, and the antisigma-plus, the same year in Rome.

The hyperons and K mesons display their unorthodox qualities as soon as they appear. More, the very existence of all these different forms of matter remains a riddle. Even granting that their existence is an obvious fact, the particles' behaviour confronts science with puzzles that all but defy solution.

Take, for instance, their decay time. The particles live 10^{-8} to 10^{-10} sec, which by the nuclear time scale corresponds to weak interactions. But we have seen that their creation follows the laws of strong interactions, which take place in 10^{-23} sec. This contradicts the principle of reversibility, according to which particles created as a result of strong interactions should decay in the same way. It would appear that hyperons and K mesons have every opportunity of decaying in strong processes. Take, for example, the neutral lambda particle. It decays into a proton and a negative pion. The energy needed for the process can easily be determined.

The mass of the Λ^0 is 74 electron masses more than the total mass of the proton and pion which, translated into

energy, yields 37 MeV. This indicates that the particle should decay with the same speed as it forms. And these formal estimates can be carried out with respect to any of the 16 particles.

But in actual fact they live 10^{14} times longer. It was this tremendous discrepancy between the expected and observed lifetimes that was responsible for the particles being called "strange", a name that has stuck.

To explain the paradox of the strange particles, some theoreticians suggested that they could appear only in groups of two or more simultaneously. The idea was confirmed experimentally and formulated as the rule of "associated production". The explanation of associated production is that the interactions that yield strange particles in some way affect several particles at once. Owing to energy dissipation such processes are nonreversible, which is the distinguishing feature of associated production.

Suppose a lambda hyperon and K meson are created in a collision of a negative pion with a proton:

$$\pi^- + p \longrightarrow \Lambda^0 + K^0$$

The law of reversibility applied to this hypothetical reaction yields

$$\Lambda^0 + K^0 \longrightarrow \pi^- + p$$

Another possibility is the transmutation of a K particle into an antiparticle. The lambda decays virtually into a pion, proton and an anti-K:

$$\Lambda^0 \longrightarrow \pi^- + p + \bar{K}^0$$

Finally, the lambda decays into a neutron and an anti-K:

$$\Lambda^0 \longrightarrow n + \bar{K}^0$$

We have thus attempted to forecast the lambda particle's future by drawing up a horoscope of sorts. But like all horoscopes it is not of much use since the reaction $\Lambda^0 \rightarrow n + \bar{K}^0$ is impossible for the simple reason that the aggregate mass of the daughter particles is greater than that of the parent ones. A careful study reveals that every possible case of associated production leads to a similar result for the isolated decay of any newly produced strange particle. It appears that the possible decay scheme requires very much energy. Therefore immediately after their production the particles

must part and speed away as quickly as possible. They escape death in strong interaction, surviving until a much less probable weak process claims them.

It should be said that at first the physicists had no experimental proof of associated production. But when the Brookhaven cosmotron began to produce strange particles in large quantities they quickly established that the rule of associated production was rigidly observed.

But perhaps associated production will in future be linked with some more fundamental law of nature? Perhaps associated production, which prohibits strong interactions involving only one particle, is an obscure manifestation of some conservation law? If strange particles can be produced only in pairs or larger numbers, then for all we know there may be various permitted and prohibited combinations of them. But before speaking of this law (which does in fact exist) we must make the acquaintance of a particle characteristic known as isotopic spin.

DOUBLETS, TRIPLETS, MULTIPLETS

To begin with, isotopic spin is not the spin of an elementary particle. Nevertheless, an exposition of it must commence with the "ordinary" spin mentioned before. Only from a rather different aspect. Imagine two isolated electrons and forget for the time being that they have wave properties: let them be plain corpuscles. Now we take these two tiny beads, which, according to quantum concepts, are completely identical, and place them in a magnetic field. Also according to quantum concepts, the direction of the spin axis will either coincide with the direction of the field or not. Now the two particles possess different energy, making it possible for us to distinguish one from the other. The purpose of this "thought experiment" is to draw the important conclusion that an electron can represent a doublet with respect to magnetic field: it can be in only one of two possible energy states. And in the absence of a magnetic field there is no way of distinguishing one electron state from the other. Physicists call this degeneracy, degeneracy of a particle into a state of indistinguishableness.

Magnetic degeneracy has played an important part in the history of physics. Remember the charge independence of nucleons. Experiments on the deflection of moving protons

and neutrons by other protons and neutrons have revealed an interesting phenomenon: nuclear forces or strong interactions between nucleons are always constant, irrespective of the nucleon combinations involved. To the extent that strong interactions are concerned, the proton and neutron behave as one particle, a nucleon. This has been mentioned before. The only way of distinguishing a proton from a neutron is by their electromagnetic interactions. If electromagnetism suddenly vanished from the universe the proton and neutron would degenerate to indistinguishableness. That is why the nucleon is regarded as a charge doublet, with the proton as one state and the neutron as the other.

The concept was first enunciated by Heisenberg, who also clothed it in refined mathematical form, thus creating a mathematical model of the nucleon including a variable with two possible values corresponding to the proton and the neutron. Heisenberg's mathematical apparatus is very like Pauli's mathematical description of electron spin and, proceeding from this superficial similarity, Heisenberg called *his* variable "isotopic spin". The qualification "isotopic" points out that the proton and neutron are essentially isotopes. They have almost the same mass, though they differ in charge. The word "spin", however, based as it is on purely external similarity, is hardly a successful choice tending to mislead the uninitiated. Which is why we started out this section with the reservation that spin and isotopic spin are not the same thing.

Spin is a motion intrinsic to particles; isotopic spin is no more than a mathematical characteristic making it possible to distinguish a proton from a neutron. At the same time the analogy with electron spin extends farther, and a nucleon's isotopic spin is also $\frac{1}{2}$. Also, like its namesake, isotopic spin can also be $+\frac{1}{2}$ or $-\frac{1}{2}$, depending on orientation with respect to a frame of reference. In quantum electrodynamics particles are usually considered in reference frames with one axis coinciding with the direction of the external magnetic field. The direction of reading for isotopic spin is also along the z axis, and its projections are denoted by I_z. Thus $I_z = +\frac{1}{2}$ corresponds to the proton, and $I_z = -\frac{1}{2}$ describes the neutron. In Heisenberg's mathe-

matical theory charge independence becomes a conservation law. In interactions of nucleons the total isotopic spin does not change. From this logically and mathematically derives the equality of the forces between a proton and neutron, a proton and proton, and a neutron and neutron. It must be said, however, that the concept of isotopic spin adds nothing to our knowledge of charge independence and is no more than a formal mathematical interpretation of this independence.

Way back, when Yukawa had just introduced the idea of pion emission and reabsorption to explain the mysteries of nuclear forces, the English physicist Nicholas Kemmer suggested that the concept of isotopic spin could be extended to pions. His reasoning was that nuclear forces, which include virtual pion exchange, are independent of charge sign, hence pions should also display charge independence. And if this is the case why not apply the concept of isotopic spin to them?

Pions possess three charge possibilities. A physicist would say that they form a charge triplet potentially capable (again assuming for a moment that all charges have vanished) of degenerating into a state of indistinguishableness.

The grouping of particles into charge doublets or triplets (or multiplets, as they are more often called) offers a convenient means of describing them. All we have to say is that a pion is a triplet whose mean charge is zero to immediately surmise that its charges are $+1$, -1, 0 ($+1-1+0=$ $=0$), and its isotopic spin is unity with the projections I_z respectively being $+1$, -1 and 0.

Similarly, when we say that a nucleon is a doublet with mean charge $+\frac{1}{2}$, we assume that its charges are $+1$ and 0 $\left(\frac{1+0}{2}=+\frac{1}{2}\right)$, its isotopic spin is $\frac{1}{2}$, and the I_z projections are accordingly $+\frac{1}{2}$ and $-\frac{1}{2}$. Taking antinucleons, they form a doublet with mean charge $-\frac{1}{2}$, isotopic spin $\frac{1}{2}$, and I_z projections accordingly $-\frac{1}{2}$ and $+\frac{1}{2}$.

The concept of isotopic spin and charge multiplets also points out another difference between pions and nucleons. Nucleons form doublets with mean charge $+\frac{1}{2}$, while the mean charge of pion multiplets is zero.

After all this we can now ask whether hyperon interactions are charge independent and whether they satisfy the law of conservation of isotopic spin. Perhaps the positive sigma hyperon is, but for electrical properties, identical to the negative or neutral particle? Do strange particles display "degeneracy"?

First of all, the sigma hyperons form a charge multiplet. In this respect they are similar to pions, and the conclusion suggests itself that they can be classified like pions or nucleons. Such a classification would mean recognition that heavy strange particles are in some way associated with nucleons.

It was accordingly postulated that hyperons are doublets with isotopic spin $\frac{1}{2}$ and mean charge $+\frac{1}{2}$ or $-\frac{1}{2}$. The K particles, apparent members of the pion family, were rated as triplets with unity isotopic spin and zero mean charge.

However, the strange particles did not tolerate the scheme forced upon them for long and seemed in a hurry to prove that they were strange in more ways than one.

Murray Gell-Mann in the USA and K. Nishijima in Japan independently of each other came to the conclusion that strange particles might refuse to fit into the scheme assigned to them. More, the hyperons' and K mesons' deviations from the scheme actually held the key to their strangeness.

But who said that hyperons were doublets with isotopic spin $\frac{1}{2}$ in the first place? Or was it simply because the particles seemed to be related in some way to nucleons that they were, for the sake of order and simplicity, ascribed properties associating them more firmly with nucleons? But it is often a long way from desire to fulfilment.

So what was the mystery of the hyperons? We can suppose that the heavy particles are not doublets with isotopic spin $\frac{1}{2}$ but actually triplets with unity isotopic spin; conversely, K particles are not triplets but doublets. This assumption already seems to outline the contours of a conservation law capable of explaining the associated production and remarkable longevity of strange particles.

THE LAW OF STRANGENESS

We have seen that a physicist has no difficulty describing families of particles. Using the "stenography" of the microworld, all he has to do is state a family's mean charge and multiplicity. The nucleon is a doublet with $+\frac{1}{2}$ mean charge, a pion is a triplet with zero mean charge: it is all very simple and clear.

Now suppose that among the hyperons we have a particle with zero isotopic spin and charge. Physicists call such particles, which have only one possible state, singlets. Well, if, for example, a neutral lambda hyperon proves to be such a singlet then its mean charge, which, as assumed before, is zero, will prove $\frac{1}{2}$ smaller than the charge of a nucleon doublet. But as, at the time, the physicists had expected hyperons to have a mean charge of $+\frac{1}{2}$, the lambda hyperon turned out to be "displaced" by minus one-half of unity charge. Gell-Mann postulated that this displacement could prove to be an important characteristic of the particle, a measure of its strangeness, as it were. Thus a new quantity appeared in physics: strangeness, which heralded one of the most important discoveries in the world of elementary particles.

It might appear to some that physicists had introduced a new word into the science without even attempting to explain an unusual property of new elementary particles. Perhaps it was no more than a gimmick? But those who have attentively followed the development of nuclear physics will hardly have such thoughts. As we shall see later on, theoreticians had resorted to such devices before which have become a method of knowledge, a key to unconventional mysteries of the invisible universe. It was thus that the concept of nucleon charge was introduced to account for the stability of atomic nuclei, and the concept of electric charge, the conservation of which seems to us an absolute and natural property only by sheer force of habit. Try and explain what *is* an electric charge!

The strangeness of all particles was measured experimentally according to the laws of particle production. It was found that only hyperons and K mesons have strangeness (denoted S) other than zero: for K^+ and K^0, $S=+1$; for K^- and K^0, $S=-1$; lambda and sigma hyperons have $S=-1$,

and their antiparticles, $+1$; xi hyperons have $S=-2$, and anti-xi, correspondingly, $+2$. It will be observed that strangeness differs from other types of charge in that it can take values of 0, ± 1 and ± 2, whereas other charges can be only 0 or ± 1. This is only a superficial aspect. Instead of strangeness one could, as has been done before, introduce a factor representing the sum of nucleon charge and strangeness. If we compound the nucleon charge ($N=1$) and strangeness of hyperons and the nucleon charge ($N=0$) and strangeness of K mesons we will find that the number $Z=N+S$ also takes on values 0 and ± 1, respectively.

It is not in numerical values that strangeness differs from charge. The difference is much deeper and lies in the very nature of matter. Unlike charge, strangeness is not always conserved. When a lambda hyperon decays into a nucleon and pion the conservation of strangeness is violated in the most flagrant manner. That such a mode of decay exists is beyond doubt, as it led to the discovery of the neutral lambda hyperon. As we already know this decay is rather out of the ordinary as the hyperon lives 10^{13} times longer than had been expected. Its lifetime is sufficient for it to travel a tremendous distance, on the nuclear scale; one centimetre. As a special interaction is responsible for slow decay, we can add to the concept of strangeness that in weak interactions strangeness is not conserved. Unlike the law of conservation of electric charge, the conservation of strangeness is an approximate law which is most strictly valid in the case of strong interactions. On the basis of the principle of charge independence we can prove the conservation of strangeness for all strong and electromagnetic interactions. In any reaction of this type the total strangeness of the particles entering the reaction equals the total strangeness of the reaction products. Now we can offer a simpler explanation of associated production. Strange particles appear in collisions of "ordinary" particles. As the strangeness of "ordinary" particles is zero the total strangeness of the reaction products must also be zero. Hence, at least two particles must be born for their strangeness to cancel out. Thus, writing down the strangeness formula in one of the reactions known to us, we have

$$\frac{p+\pi=\Lambda^0+\mathrm{K}^0}{0+0=-1+1=0}$$

and the strangeness is conserved at zero.

As mentioned above, only weak interactions do not satisfy strangeness conservation and, as we shall see later on, another, more fundamental conservation law is also violated in weak interactions.

As the "inventor" of strangeness, Murray Gell-Mann, wrote, we do not know whether there is any deeper connection between these laws and their violations. In any case, it is apparent that nature conceals many important secrets in weak processes and one of the main tasks facing physics is discovery of the laws governing these processes.

"Strangeness" has been explained in more or less simple and logical terms, but there are still many mysteries in the strange world of elementary particles. Yet it exists not as a whim of nature designed to baffle us with puzzles. Its existence is associated in intimate ways with properties of matter that remain hidden from us by impenetrable veils. Perhaps at very small distances, smaller than those man has succeeded in achieving with the help of his greatest accelerators, processes of an unknown nature take place. But this is for the future to see. For us it is high time to finish our story of strange particles.

And so, hyperons and antihyperons.

Within a time interval of 10^{-10} sec, these particles (with the exception of the Σ^0) manage to undergo the following decays:

$$\begin{array}{ll} \Lambda^0 \longrightarrow n + \pi^0 & \Sigma^0 \longrightarrow \Lambda^0 + \gamma \\ \Sigma^+ \longrightarrow n + \pi^+ & \Lambda^0 \longrightarrow p + \pi^- \\ \Sigma^- \longrightarrow n + \pi^- & \Sigma^+ \longrightarrow p + \pi^0 \end{array}$$

We already know that strangeness is violated in these decays: as the strangeness of nucleons and pions is zero, the strangeness changes by unity.

The heaviest xi hiperon decays according to the scheme:

$$\Xi^- \longrightarrow \begin{cases} \pi^- + \Lambda^0 \\ \pi^0 + \Sigma^- \\ \pi^- + \Sigma^0 \end{cases}$$

The Ξ^0 decays similarly. But no one has yet observed the transmutation of a xi hyperon into a nucleon, although from the energy aspect the process is feasible and there appears to be nothing to prevent the decay

$$\Xi^- \longrightarrow n + \pi^- + \pi^0$$

This is probably not accidental. And although strangeness in weak interactions is not conserved it cannot, nevertheless, change at random. Thus, a change of two units appears to be impossible, and we can define the law of conservation of strangeness more accurately by saying that in strong interactions strangeness is conserved while in weak ones it changes by unity.

This law is consistently obeyed by all the known representatives of the "strange" world.

Now it becomes finally clear how a hyperon is produced. When a nucleon passes by another nucleon both particles remain in each other's vicinity for too short a time for the reverse reaction of a weak decay to take place, when a nucleon can turn into a lambda hyperon with the absorption of a pion from its neighbour's shell.

In a collision of nucleons a hyperon can be produced only in a strong process, i.e., only with the strangeness conserved. That is why a hyperon is created together with a positive K meson.

A xi hyperon can be bred by a nucleon without violating strangeness only together with two K mesons, but this process is observed rather rarely.

In principle the production of a xi hyperon and one K meson is possible in the collision of a lambda or sigma hyperon with a nucleus, but as these hyperons appear rarely production of a xi particle requires a powerful beam of hyperons.

As hyperons display some similarities with nucleons (they are sometimes classified together as baryons) it is natural to expect them to display beta decay:

$$\Lambda^0 \longrightarrow p + e^- + \tilde{\nu}$$
$$\Sigma^- \longrightarrow n + e^- + \tilde{\nu}$$

The electrons produced carry tremendous energies, sometimes in excess of 100 MeV. It appeared of interest to study decays at such high energy. Suffice it to say that it was thanks to such energetic electrons that Hofstadter was able to determine the size of a nucleon. Electrons were expected to tell a lot about the hyperon's structure, but to the physicists' great disappointment hyperon decays were so rare that in the course of several years only about 20 events of beta decay of lambdas and only a few events of sigma hyperon decay were observed.

This despite theoretical predictions! Which gives rise to another mystery: why do hyperons emit electrons so rarely and so unwillingly?

In the case of xi hyperons beta decay has still to be observed. To some degree this can be explained by the fact that few xi hyperons have been produced, yet this strange prohibition of beta decay suggests the existence of some deeper intriguing mysteries.

Another unanswered question is why hyperons do not decay with the emission of muons. Hyperons have a large mass and ample energy for such decay. It has been suggested that hyperons represent a special excited state of nucleons, just as muons are perhaps simply excited electrons and nucleons and antinucleons are the same kind of matter in different excitation states.

Whatever problem we take, a penetrating investigation leads us to an unknown hypothetical particle capable of breeding different elementary particles in different excitation states.

An interesting phenomenon involving hyperons was discovered in 1953 by Polish physicists Marian Danysz and Jerzy Pniewski. Occasionally under the impact of a fast particle a cracked nucleus may emit, along with nucleons and mesons, particles which quickly eject a pion. When the strange phenomenon was thoroughly studied it was found that the ejected fragment represents a nucleus of a light element in which one of the neutrons is replaced by a lambda hyperon. Such nuclei were called hypernuclei or hyperfragments. Some unusual hypernuclei were discovered: ${}_{\lambda}H_1^4$ (a superheavy hydrogen isotope), ${}_{\Lambda}He_2^5$ (a formerly unknown helium isotope), along with heavy nuclei in which one neutron is simply replaced by a hyperon, such as ${}_{\lambda}H_1^3$ (hypertritium) and others. Hypertritium is radioactive, emitting a pion in 10^{-10} sec. Today hypernuclei up to nitrogen are known. But, strange as it may seem, the simplest possible hypernucleus —a lambda hyperon-proton system (hyperdeuterium)—has not been discovered. These particles are incapable of being bound in a nucleus owing to the insufficiency of their interaction forces. One more particle, a neutron, is required to form a comparatively stable system, hypertritium.

Our story of strange particles ends with K mesons. The first single heavy meson with a mass of around 900 electron masses was observed in 1941 by Le Prince-Ringuet; later,

after 1949, several particles of like mass were discovered mainly in Powell's laboratory. Subsequently the remarkable equality of the masses of all K mesons within the precision of the experiment was discovered. The closest value is accepted at 966. From this, as well as the similarity of other K meson properties, the hypothesis arose that we have here a single particle capable of decaying in different modes.

K mesons introduced physicists to many new phenomena, their properties are diversified and differ from those of lighter mesons, pions. Created in strong interactions together with hyperons, they are also capable of appearing in pairs (K^+ and K^-, K^0 and $\overline{K^0}$). All K mesons are radioactive and decay into two or three particles (π, μ, e, ν), usually with a lifetime of the order of 10^{-8} sec.

A characteristic feature of slow K meson decay is its remarkable diversity. As K^+ particles are strongly absorbed by nuclei they have been fairly well studied and can be used to trace the diversity of K meson decay modes. A positive K meson can decay in one of seven modes:

$$K^+ \longrightarrow \left\{ \begin{array}{ll} \pi^+ + \pi^0 & 2\pi \text{ decay} \\ \left.\begin{array}{l} \pi^+ + \pi^0 + \pi^0 \\ \pi^+ + \pi^+ + \pi^- \end{array}\right\} & 3\pi \text{ decay} \\ e^+ + \nu + \pi^0 & 3e \text{ decay} \\ e^+ + \nu & 2e \text{ decay} \\ \mu^+ + \nu + \pi^0 & 3\mu \text{ decay} \\ \mu^+ + \nu & 2\mu \text{ decay} \end{array} \right.$$

The accepted names of the decay modes in the right-hand part of the scheme are $K^+_{\pi 3}$—3π decay, $K_{\mu 2}$ — 2μ decay, etc.

These decay modes are characteristic of both the negative and neutral K meson. No other particle in the microworld can boast such remarkable diversity. It took many heated discussions and many verification tests before it was proved that the assorted decay modes all belong to the same particle.

It was the K meson, the neutral K meson, to be more precise, that was destined to undermine one of the fundamental laws of nature, the law of conservation of parity. But before parting with the K meson we must take a look at some of the properties of the K-zero and anti-K-zero mesons, which are diverse indeed and differ markedly from those of other neutral particles.

The K-zero meson is not an absolutely neutral particle, and the K^0 and $\overline{K^0}$ are not identical. At the same time, they are capable of spontaneously transmuting into one another. Thus, a K^0 produced in, say, the collision of a pion with a proton will as it were "oscillate" for a while, turning into its antiparticle and back again several times. In this sense a particle produced initially as a K-zero meson is dual, alternating from $\overline{K^0}$ to $\overline{K^0}$ and back. Hence, in their production and reabsorption K-zero mesons must behave as absolutely neutral particles. This is the case in decay events, in which neutral K mesons appear as two absolutely neutral particles, though their lifetimes can, of course, vary. Their masses differ too, albeit by one hundred-thousand-millionth of a fraction. They are often even denoted not as K-zero and antiK-zero ($\overline{K^0}$ and $\overline{K^0}$) but as K-one-zero and K-two-zero (K_1^0 and K_2^0).

THROUGH THE LOOKING GLASS

We now return to the problems of "right-handedness" and "left-handedness", of the neutrino and antineutrino, and of weak interactions. It was this class of interactions that provided physicists with some of their most wonderful experiences. For the first time they enabled man to peek into the miniaturized "cosmic" space of the microworld and see it as it really is.

As is known, as a result of collisions between high-energy particles many unstable byproducts are formed in the strong interaction domain. Weak interactions were "mobilized" to clear the battlefield with the aid of slow decays for new powerful collisions, for new nuclear encounters.

It all began in the recent past when physicists were racking their brains over the mysteries of strange particles, and the notion that one and the same particle could decay in different ways was only dawning behind the mist of various hypothetical propositions.

Two strange particles decayed into pions: one into three, the other into two. Since at the time it was thought that different decay modes meant different particles, the former was dubbed a tau meson (τ), the latter a theta meson (Θ). Almost at once it was found that the properties of tau and theta are completely identical and all their parameters

coincide: mass, relative breeding frequency in different interactions, lifetime.

Today we know that they are one particle, the K meson, but the designations τ and Θ remain to denote particles with a three- and two-meson decay scheme.

The idea of various modes of decay for the same particle was easy to accept: after all, various modes of decay of radioactive nuclei are known. But there was another feature which defied explanation. Before going into it, however, we must introduce another law of the microworld, the law of conservation of parity.

This law states that the wave function of an elementary particle conserves either positive or negative parity.

Physical parity characterizes the symmetry of particles with respect to right and left in space and their behaviour in a mirror substitution of right for left and left for right. Such a substitution (inversion) requires a change in the sign of spatial coordinates x, y, z and it is equivalent to a mirror reflection.

Thus, if we place a sphere in front of a mirror we find that it is in every way identical to its mirror image, which is to say that it is a mirror or reflection symmetrical object. But if we take a screw we will readily notice that the mirror image has a left-handed thread where the real object is right-handed. The human body, screws, mollusk shells and most other physical bodies do not possess reflection symmetry. Similarly to reflection symmetrical and reflection asymmetrical objects, quantum mechanics distinguishes between positive and negative spatial parity.

It is seen from this that nonconservation of parity denotes that the symmetry or asymmetry of an object depends not on its nature but on the coordinate system in which we are considering it: this or that side of the looking glass. But the only difference between them is that right has become left and vice versa. Hence, nonconservation of parity suggests the inequality of "right" and "left" in space. This is something common sense rebels against, and this instinctive revulsion is confirmed by numerous experiments in the domain of strong interactions, where the conservation of parity is as inviolable as the conservation of mass.

Be that as it may, but the "tau-theta mystery" had to be resolved. Of course, it would have been simple to assume that here was a case of decay of different particles and pr-

serve the parity principle. But the particles behaved so alike that there was nothing to suggest any difference between them.

It is not an easy thing to declare that twice two isn't four even if you are quite sure of it. This was the situation in which two young Chinese theoreticians and future Nobel Prize winners working in America, Tsung Dao Lee and Chen Ning Yang, found themselves. But they did as much, postulating that the explanation of the "tau-theta mystery" lay in the breakdown of spatial parity in weak interactions. Moreover, they suggested the experimental verification of the hypothesis.

The idea was to find a way of polarizing the particles or nuclei produced in beta decay so as to establish the preferred direction of electron emission: in the direction of the spin axis of the disintegrating particle or against it. Toward the end of 1956, a team of physicists headed by Miss C. S. Wu performed the experiment. In it radioactive cobalt-60 was cooled to a temperature approaching absolute zero and placed in a magnetic field with the purpose of orienting the particles' spins in the same direction.

Theoreticians all over the world impatiently awaited the result of this fine experiment. Confidence in the universal nature of the parity principle was so great that some of the greatest physicists of our time refused to contemplate its breakdown. Thus, only two days before the experiment was completed Wolfgang Pauli declared: "I don't believe that God is a weak left-handed being and will wager any sum that the experiment will confirm the parity principle." It remains unknown whether any one accepted the wager or not, but Pauli would have lost. Lee and Yang's theoretical prediction was brilliantly upheld, and the law of conservation of parity was found to break down in the domain of weak interactions. Left and right were found to be unequal directions. Shortly afterwards additional confirmation was produced in works on pion and muon decay carried out at Columbia and Chicago Universities. Parity also broke down in the decay of a charged K meson into a muon and neutrino.

But before parity could finally be done away with in weak interactions one more problem had to be solved. The thing is that all the processes where parity was shown to break down had one thing in common: among the end decay products there was always present at least one neutrino. Hence, there was still the chance that the violation of pa-

rity was due to the neutrino which, as mentioned before, had already salvaged one of the fundamental laws of physics. But perhaps it was asking too much of the neutrino to repeat its feat?

A point of interest was that the neutrino had no part in the "tau-theta mystery". Moreover, although this was the process that had sparked the described events, the breakdown of parity in this case had been proven only indirectly. Thus it became necessary to prove the violation of parity for at least a single process not involving neutrinos. Only then could it be claimed with full justification that violation of parity is characteristic of all weak interactions without exception.

These experiments were staged in the spring of 1957.

A beam of high-energy negative pions was aimed at a proton target. The collision of a pion with a proton was expected to produce two "strange" particles, a Λ^0 and a K meson.

A decaying Λ^0 particle usually produces a negative pion and a proton. By mentally passing a plane through the path of the initial pion and of the Λ^0 particle one can trace the direction of flight of the pion created in the Λ^0 decay. Of all possible directions of flight we are interested in two: up or down from the imaginary plane. But where is up and where is down? We can agree that up is indicated by the direction in which the thumb of the right hand points when the index finger is directed along the path of the initial pion and the middle finger is along the Λ^0 path. Of course, the same could be done with the left hand, and our up and down would change places, but we are concerned simply with distinguishing one direction from the other. Thus, if the law of parity is valid and nature has no preferential direction the newly created pions will be emitted upwards and downwards with equal probability. The experiment did not confirm this, and according to the right-hand rule the pions preferred to fly upwards.

Thus it was finally shown that nature does have preferred directions, that right is not equal to left or up to down. But is this as meaningless as seems at first glance?

SAVE SYMMETRY AT ALL COSTS

Immediately after Yang and Lee's discovery, Academician Lev Landau pointed out that symmetry, far from hav-

ing vanished, had become more natural. His conclusion was that absolute symmetry is possible only in the absence of fields. Hence the real world must be asymmetrical. This is an intrinsic property linked with the "inequality" of particles and antiparticles. After all, we live in a world where protons and neutrons predominate over antiprotons and antineutrons.

Let us continue our thought experiments begun in connection with the "right-left" problem by imagining a mirror endowed with certain magic properties: it not only reflects an object but also substitutes an antiparticle for every corresponding particle. That is to say that it effects what physicists call charge conjugation.

What is such a mirror good for? The thing is that in weak interactions not only direction matters but also the particles taking part in an event: particles or antiparticles. As a physicist would put it, weak interactions are not invariant with respect either to spatial inversion or to charge conjugation.

But if both operations are carried out simultaneously, i.e., right and left are interchanged and particles are replaced by corresponding antiparticles, the properties of the system, as we already know, do not change.

To clarify this we must return to our analogy with the reflection of mirror-asymmetrical objects. When we look at a mirror our heart is on the right side and a left-handed screw has a right-handed thread. But if we repeat the reflection once more the heart returns to the left side and the screw becomes left-handed again. The image, in fact, will be identical to the original object.

Similarly, symmetry properties will be retained in any system in a replacement of left by right and particles by antiparticles. Lev Landau called this property combined parity.

From the conservation of combined parity derives another rule. All weak interactions, it works out, are indifferent (invariant) with respect to time inversion, which is to say that the description of an event does not change if future is replaced by past. This makes it possible, for example, to compute the probability of A and B being created in a collision of C and D if we know the probability of the reverse process of C and D being created in a collision of A and B.

A. I. Alikhanov, G. P. Yeliseyev and V. A. Lyubimov proved experimentally (to an accuracy of several per cent) the conservation of temporal and, consequently, combined parity.

Combined parity has shed a ray of light on the darkest section of the maze of the microworld where neutrinos and antineutrinos reside. It was established that, like photons, they have no rest mass and the spin axis of one particle is always coincident with the direction of motion while that of the antiparticle is opposite.

It became clear that if, in combined inversion, we "change" particles into antiparticles and left into right, the sense of polarization must change as well. It was no easy matter to determine the sense of polarization for neutrinos and antineutrinos, but after numerous experiments physicists finally established that neutrinos are polarized in the direction opposite to motion and antineutrinos, in the direction of motion. This is to say that the axis of neutrino spin is directed against the line of motion and the axis of antineutrino spin is with the line of motion.

It is legitimate to ask: if spatial parity is not conserved in weak interactions, why should it be conserved in strong or electromagnetic interactions? The answer to this question was given by a young Soviet scholar, V. G. Solovyov.

Spatial parity is conserved only in electromagnetic interactions and in strong interactions involving neutral pions. Why? This is easily answered. The photon and neutral pion are the only particles that have no antiparticles, or rather, they are their own antiparticles. Hence, a change of charge means nothing to them and, consequently, left and right are equal.

But when strange particles take part in strong interactions parity falls, and this being the case, insofar as strange particles appear even in intermediate states of strong interactions, spatial parity must also fall.

To sum up, instead of the law of conservation of spatial parity nature goes by the law of conservation of combined parity. And the equality of right and left? Is it merely a special case, a consequence of the identity of some particles with antiparticles? Until very recently the answer to this question would have been an unequivocal yes.

In replacing parity conservation with combined parity conservation, or C-P invariance (C for change in charge sign, P for right-left shift), physicists had obviously paid too low a price to the strangenesses of the microworld. There is probably no other physical concept in history which offers such vivid illustration of the dialectical law of negation as the evolution the parity principle is undergoing before our very eyes.

Landau's combined inversion suited everyone. First we had unjustifiably violated the world symmetry by considering matter alone without relation to antimatter. This was the case until physicists were faced with the tau-theta enigma. Landau had apparently resolved it. But then, in July 1964 four American workers James A. Christenson, James W. Cronin, Val. L. Fitch and René Turlay, published a work in which they set forth the results of experiments with K_2^0 mesons whose decay events displayed what appeared to be a violation of C-P invariance. The Ks had presented a new surprise.

If the law of conservation of combined parity is valid, then K_2^0 decay must follow the scheme:

$$K_2^0 \longrightarrow \pi^+ + \pi^- + \pi^0$$

In the experiment, however, the K_2^0 decayed into only two pions, one positive and one negative. But combined parity prohibits such a decay.

In a series of experiments with beams of K_2^0 mesons aimed at verifying the conservation of C-P invariance in their decay, writes Cronin, 22,000 events of K_2^0 decay were examined, and in 45 of them deviations from the law of C-P invariance were observed. The decay products were registered with conventional magnetic field deflection systems coupled with spark chambers and Cerenkov counters. The effective masses of the two resultant pi mesons were measured, and it was found that the initial mass was equal to the total mass of two, not three, pi mesons. There could be no question of other K particles, the K_1^0, for example, being involved, as the experiment was carried out 20 metres from the accelerator, a distance at which any K_1^0 must surely disintegrate.

The only apparent explanation of the observations was that this was a violation of C-P invariance. However, the researchers felt that it was still too early to draw sweeping conclusions and stated their intention to carry out a new series of experiments which could shed light on this interesting property of particles or space.

If these experiments fail to provide a sufficiently clear-cut explanation of the phenomenon the problem will be a grave one. Perhaps even more grave than the tau-theta riddle. It is interesting to note that K mesons have as it were served to focus all the basic contradictions of the microworld, its strange quantum-mechanical manifestations.

The experiments carried out at Princeton show that there exist processes the mirror images of which cannot exist in the antiworld, suggesting that nature is evidently not as symmetrical as had been assumed till now.

Naturally enough, almost as soon as the paper was published works appeared aimed at salvaging the fundamental concept of the invariance of nature. One interesting hypothesis sought to explain the K meson experiments by introducing an unknown "fifth force". It will be recalled that as of today four forces are known: nuclear, electromagnetic, weak and gravitational. And all four are indifferent to the direction of time.

Now the K meson experiment confronted physicists with a cruel dilemma: either to abandon existing theoretical notions, or salvage them by sacrificing invariance with respect to the flow of time.

A score or so hypotheses have already been postulated in an effort to save time invariance. One of them holds that the prohibited decay into two pions is the first tangible manifestation of the fifth force, which is even weaker than gravitational.

The fifth force manifests itself in different ways in our world and the antiworld. When it has "conventional" matter as its source it has one sign, when it is associated with antimatter it is of opposite sign.

Assuming our Galaxy comprise "ordinary" matter (and this is most likely the case), then practically the whole potential of the fifth force on the surface of the earth is due to "ordinary" matter. In all our experiments it affects antiparticles and particles differently. Obviously this force

is postulated to be of just the right intensity and asymmetry to account for the observed probability of neutral K_2^0 mesons transmuting into neutral K_1^0 mesons, which can decay into two pions without violating the C-P invariance.

This ingenious *ad hoc* hypothesis can be verified by boosting the energy of decaying K_2^0 mesons. If the fifth force does not possess any very outlandish unforeseen properties ("behaves itself", as physicists say), then the number of two-pion decay events should increase one-hundredfold when the K meson energy is increased tenfold, as follows from the fundamental laws of quantum mechanics.

Experiments carried out independently by two research teams in Switzerland and England yielded an unequivocal answer: the probability of two-pion decay is not altered by increasing K_2^0 meson energy from one to 10 GeV. This does away with the "fifth force" postulate, as clearly decay into two pions is not due to any transmutation of a K_2^0 into a K_1^0. Rather, the baffling decay is a consequence of a genuine violation of the law of conservation of combined, and hence temporal, parity. Apparently one of the fundamental conservation laws will have to be ditched. This will doubtlessly have far-reaching consequences for theoretical physics.

In what direction will this important problem evolve? In June 1965, a session of the Nuclear Physics Department of the Soviet Academy of Sciences devoted to elementary particles was held at Dubna. It was opened by I. Yu. Kobzarev, who presented a review of the situation in which he spoke of the possibility of violation of charge parity in electromagnetic interactions. Not weak interactions, mind you, but electromagnetic, apparently one of the most tranquil domains of modern physics! Conservation of charge parity, it will be recalled, means that for any particle interactions differ only in charge sign. In most cases this is so. But lately physicists have begun to suspect that charge parity may be violated in electromagnetic interactions. If this is so then we will have a natural explanation of the Princeton effect of C-P violation, and, consequently, the relative rarity of the $K_2^0 \to \pi^+ + \pi^-$ decay will be provided with a logical explanation. The final word, as usual, now rests with the experimenters.

The discovery of asymmetrical decay of cobalt-60 nuclei in a magnetic field not only forced physicists to revise the law of parity, known since Leibnitz's time, and review the question of the properties of space. It also opened up opportunities for a more thorough study of the properties of muons.

Theory predicts the magnetic moment of electrons to a high degree of accuracy. It was interesting, therefore, to try and measure a muon's magnetic moment to check the applicability of electromagnetic theory to it. Any deviation from the predicted value would shed light on muon structure.

Violation of parity in weak interactions made it possible to use an accelerator to produce a muon beam with a dominantly oriented spin of the particles. In muon decay into an electron, neutrino and antineutrino the electrons were expected to fly out in the direction opposite the muon spin. This provided physicists with an excellent opportunity not only of orienting the muons but also of determining this orientation by the decay electrons.

The planned investigations also held promise of answers to a number of other questions of primary importance, such as the applicability of electromagnetic theory to very small space domains. An answer to the question about the distances over which electromagnetic forces act would supply physicists with invaluable information on the nature of the microworld. Notably, they would be in a position to verify Heisenberg's bold hypothesis concerning the structure of space and time. In this hypothesis the German physicist postulated that time and space are not the continuums they have been held to be but are in fact discrete, discontinuous. Hence, there must exist a segment, a kind of quantum of length, evidently much smaller than any length man has ever had to deal with. At distances smaller than this length (which are simply impossible) even thought experiments are inconceivable.

Similarly, there must exist a time quantum, the smallest time interval in which any process can take place. Theoreticians expect that the time quantum could hardly be smaller than 10^{-40} sec.

Now we can go back to the muon. The unit of strength

of the magnetic moment of a particle is the magneton. The ratio of the spin magnetic moment in magnetons to the spin moment produces a term called the **g-factor.** There is no need for us to go deep into this difficult concept, which would require an extensive explanation. For our purposes it is sufficient to remember that there is such a thing as the *g*-factor—and that's all.

It was Dirac who predicted that the *g*-factor of the electron was equal to 2, and this was confirmed by experiments of that time.

Shortly after World War II more precise experiments performed at Columbia University indicated that the *g*-factor of the electron differed from 2 by about one part in 1,000. Not much, it would seem, but the departure, which became known as the anomalous magnetic moment of the electron, worried the physicists. This lasted until the anomaly was explained in terms of the known effect of emission and reabsorption of virtual photons by the electron.

It was natural to see if the muon also displayed a similar phenomenon. Since 1957, several experiments were undertaken to measure the *g*-factor of the muon as precisely as possible. The simplest approach is to measure the magnetic moment directly, which can be done to an accuracy of one part in 100,000. Theory, however, does not predict the moment directly; it predicts only the *g*-factor, and this prediction requires knowing the mass of the muon. This measurement is still limited in accuracy to about one part in 10,000. As a result the experimental value for the *g*-factor is limited to the same order of accuracy. Since the deviation of the *g*-factor from 2 is only one part in 1,000, a measurement accurate only to one part in 10,000 leaves an uncertainty of 10 per cent, which is much too large to enable definite conclusions to be reached with respect to such an important phenomenon.

More recently a direct measurement of the muon's magnetic moment was carried out at Columbia University. The mass of the muon was found to be 206.76 ± 0.2 times the mass of the electron. While this is a remarkably precise value as mass measurements go, it still leaves an uncertainty of 10 per cent in the value of the *g*-factor.

Quite a different way to get at the *g*-factor was taken in a remarkable experiment at CERN (European Council

for Nuclear Research) that required more than three years to carry out from conception to final completion early in 1961. The experiment showed that the g-factor of the muon is 2.001145 ± 0.000022. The theoretical prediction was 2.001165. Experiment therefore confirmed, to an accuracy of 1 per cent in the anomalous part of the g-factor, that the muon behaves exactly like a heavy electron. Recall the hypothesis that the muon is an excited electron. The circle is thus closed and theory has to be revised. New ideas concerning the structure of space and time are needed.

Measurement of the g-factor of the muon shed light on another important point. The obtained result implies that there is no breakdown in the laws of electromagnetism down to distances of 7×10^{-14} centimetre and no fundamental quantum of length, if any, greater than 2×10^{-14} cm. Hence, the quest for the quantum of length must continue in domains below the threshold of 10^{-14} cm.

The mystery of the muon has developed into a major problem which so far defies solution. The only hope is that new experiments with high-energy muons will enable physicists to advance further into the unknown.

Not so long ago we could have claimed that the story of strange particles concludes the review of denizens of the microworld. Lately, however, new events have been stirring in the physics of nuclear particles. They are caused by results obtained in probing nucleons with high-energy electrons. Physicists observed that some details in the electromagnetic structure of nucleons are such as to suggest that the meson cloud connected with the nucleon should contain, besides pions, two new kinds of mesons. The view was expressed that there are many more elementary particles than had ever been supposed, but this no longer worried anyone. It had become clear that the road to unity lay through diversity. The more new elementary particles we discover the more successful will our attempts be to draw a unified picture of the world.

And so, two new kinds of mesons were discovered. One exists in three forms, positive, negative and neutral, and decays into two pions; the other has only a neutral form and decays into three pions. The new mesons live only about 10^{-22} sec and can therefore be detected only by the end decay products.

The new particles could be detected only as a result of a painstaking analysis of pairs and trios of pions created in collisions of high-energy particles. A method frequently employed by physicists in such cases is the finding of "resonances": energy values that have a tendency to recur frequently in disintegrations. Thus, back in 1960 the two-pion resonance at an energy of 750 MeV was discovered. It could be regarded as testimony of the existence of a particle with mass equal to 1,460 electron masses. It was called the **rho meson** (ρ) and its properties proved just right to explain the results of experiments in probing nucleons with fast electrons. Several months afterwards results of experiments launched to detect three-pion resonances were published. The first resonance was found in the energy domain of 770 MeV. On this, it would seem, the search could be ended. Two new mesons had been entered in the table of elementary particles (the second was called an **omega meson**—Ω), what else was needed?

The omega meson, however, displayed some inconsistencies. For some reason its mass exceeded the value predicted on the basis of nucleon structure. A team of American physicists headed by A. Pevzner undertook a new series of searches for three-pion resonances. Their painstaking work was crowned with success and the discovery of one more three-pion resonance corresponding to a particle of 1,100 electron masses and named **eta meson.**

Thus, having embarked on a quest for two particles the physicists discovered three. This confronted the theoreticians with some difficult problems. In fact, it has placed on the order of the day a new theory of nuclear forces and nucleon structure which would take into account the existence of rho, omega and eta mesons. And, last but not least, these particles are three additional steps up to the summit which is a general theory capable of bringing all elementary particles together in a unified system.

TABLETS OF THE MICROWORLD

In our accounts of various ideas and conceptions we have made ample mention of the conservation laws. The time has come to speak of them in greater detail. The reader will perhaps have observed that, despite the diversity of

elementary particles, their transmutations obey certain laws. Heavy particles cannot spontaneously become light, electrons cannot turn into photons, etc. Why is it so? There is a classical law in physics called the **law of conservation of electrical charge.** Whatever the transmutations and transformations involving various particles, the algebraic sum of their electrical charges remains unchanged. That is why a collision of electrons does not produce photons or neutrinos, which are electrically neutral. But when an electron collides with a positron the algebraic sum of their different charges is zero and the annihilation products can well be neutral.

By analogy with the law of conservation of electrical charge there should evidently be a law prohibiting the transmutation of heavy particles into light ones. A collision of a proton and electron does not produce a positron or photon, although electrical charge conservation permits the reaction. This was explained by the concept of **nuclear, or baryon, charge.** Like electrical charge, baryon charge can be positive, negative or neutral: protons and neutrons have a baryon charge of +1, antiprotons and antineutrons, —1, leptons and mesons, zero. The importance of the **law of conservation of baryon charge** will be understood if one imagines what it would have been like without it: there would be no such thing as stable nuclei, and perhaps no such thing as atoms at all.

For light particles Ya. B. Zeldovich introduced the concept of **neutrino charge** and its corollary, the **law of conservation of neutrino charge.** The neutrino charge of an electron and neutrino is +1, of a positron and antineutrino it is —1. According to the law of conservation of neutrino charge, a muon can disintegrate into an electron, neutrino and antineutrino but not, say, into an electron and two neutrinos, although the two former laws allow it.

These three laws of charge conservation are like the three elephants which the ancients thought supported the world. They determine the possible transmutations of elementary particles and knowledge of them sheds light on the very important question: What is the difference between particles and antiparticles?

Now we can define an antiparticle as the twin of the respective particle with the signs of all three charges reversed.

We also know that not every particle has an antipode. There is no way to distinguish between photons bred by electrons and by positrons. The quantum of light is a genuinely neutral particle, one which is its own antiparticle; the same holds for the neutral pion. But how does this connect with the conservation laws?

A glance at a table of elementary particles reveals that the genuinely neutral particles have all three charges, electrical, nuclear and neutrino, equal to zero. And zero is zero in whatever system. Which is why there is no difference between a photon and antiphoton.

It must be conceded, however, that there is an element of formalism in our narrative. For we have not said a word about why the conservation laws are as just listed and not of some other nature. Nor is this an idle question. On the contrary, it is an extremely important one and it probably hides a very important and, maybe, very simple phenomenon. As of today, however, and perhaps for a long time to come, we must accept the conservation laws as something preordained. This refers in the first place to electric charge conservation.

In respect of the conservation of nuclear and neutrino charge an interesting consideration is involved, for, in the literal sense of the word, there is no such thing as a nuclear or neutrino charge. There is only something we call a charge by analogy with electrical charges.

Let us investigate this on the example of the law of conservation of nuclear charge. The definition of this law must not contradict the observed phenomena of annihilation. We can therefore agree at once that, just as in an algebraic equation we can eliminate all identical monomials of opposite sign, we shall, in counting our nucleons, simply eliminate all nucleon-antinucleon pairs. This obliges us to take all antinucleons with the minus sign. But a negative number of particles, or rather antiparticles, contradicts everyday habit, for it is as if we were counting real objects and obtaining a negative number. It is simply not very convenient. From this arose the analogy with charge. And in speaking of the number of nucleons or antinucleons we employ the concept of "charge" ascribed to them.

Now the neutrino, or, as it is also called lepton, charge. The law of conservation of lepton charge is invoked to permit neutron decay with the emission of an antineutrino

(or beta decay of some other nucleus):

$$n \longrightarrow p + e^- + \bar{\nu}$$

and prohibit the decay scheme

$$n \longrightarrow p + e^- + \nu;$$

to permit the decay scheme

$$\pi^+ \longrightarrow \mu^+ + \nu$$

and prohibit the decay scheme

$$\pi^+ \longrightarrow \mu^+ + \bar{\nu}, \text{ etc.}$$

Lepton charge is ascribed, naturally, to leptons. Antineutrinos, positrons and positive muons have a lepton charge of +1; the corresponding antiparticles, —1. All other particles have no lepton charge: for them it is zero. The role of lepton charge is not very clear. In fact, it cannot be said for sure whether it has any right to exist at all. This is linked with the existence of the muon neutrino and electron neutrino.

The experiment mentioned above showed that in the decay events

$$\pi^+ \longrightarrow e + \nu_e$$

$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$

two different types of neutrino are emitted, which makes it necessary to introduce two types of lepton charge. The question is, how correct is this?

The charge conservation laws introduce certain restrictions on the uncertainty and contradictoriness of the term "elementary particle". As we have had ample opportunity to see, most particles are far from elementary. What is the essence of the restrictive measures of the conservation laws?

Take nucleons, for example. A neutron transmutes into a proton, a proton into a neutron. In the former case the proton is, from a purely formal point of view, "more elementary", in the latter the neutron is. But when we take both events together we must concede that neither particle is quite elementary. Thus, we are unable to state for sure just how many protons, neutrons and binding pions there are in a nucleus. But, applying the conservation laws, we can say that the number of nucleons (i.e., the nucleon charge, equal, naturally, to the mass number) is quite spe-

cific. The charge of the nucleus is also definite. From this stems the curious conclusion that the nucleon concept is more in accord with the properties we ascribe to elementary particles than the concepts of neutron and proton taken separately.

In the same way, a lepton is a "more elementary" particle than, say, an electron or positron. An electron in its normal state is surrounded by a "cloud" due to the fact that electron-positron pairs are continuously being created and vanishing around it. We could even call an electron a system in which the number of electrons and positrons is changing continuously. But the system's lepton and electrical charge is constant, which enables us to speak of the system as of an elementary particle.

Proceeding one step further, if strangeness were conserved as rigidly as charges it could also be designated as a kind of fourth charge determining the number of hyperons.

But, as we have seen, strangeness sometimes breaks down. The hyperon can, albeit rarely, transmute into a nucleon and a pion. That is why, from the point of view of exact theory, the hyperon cannot be considered separately and we must classify it as a nucleon. On the other hand, in many problems, where weak decays can be neglected, strangeness can be treated as a charge.

It is now clear that electrical charge alone determines not only the number of charged particles but also, according to Coulomb's law, the acting force between them. All other laws serve only for counting particles.

PART THREE

At the Threshold of a Unified Theory

TOWARD THE FOUNDATIONS OF WORLD UNITY

"All elementary particles are so to say 'made' of the same substance, which can be called simply 'energy' or 'matter', and their ability to transmute into one another must derive from a simple law of matter." These words belong to Werner Heisenberg.

From ancient times man has been dreaming of a single material cause of all existing things and seeking to visualize "building blocks" of the universe. People felt instinctively that such a primary matter must exist.

Again and again it seemed that this primary substance had been found, but as time passed it was proved illusory. And again scholars accumulated facts which ultimately toppled yet another edifice of hypotheses. But in the process science steadily grew stronger and stronger.

What, it seemed, could have been more convincing than the mechanical world picture created by Sir Isaac Newton? It was not long before people assumed that physics was a science without a future, that it explained everything, embraced everything, was simple and logical. It simply had nowhere to evolve.

But then electricity and magnetism appeared, a higher matter devoid of rest mass and refusing to obey classical mechanics. Then it was discovered that no body can travel faster than 299,776 kilometres per second. And Newtonian mechanics became but a special case of relativistic mechanics, the mechanics of sublight velocities. Again it was necessary to assemble scattered and inexplicable facts to build up a unified theory, this time on the basis of electromagnetic field. But the discovery of neutrons and mesons complicated the task.

In the nineteen-twenties renewed attempts were made

to create a unified world picture on the basis of a geometricized field theory. The success of relativity theory engendered attempts to link gravitation and electromagnetism together, but elementary particles were left out of the picture. The geometricized theory soon proved insolvent, and the atomic picture of the physical world with its twelve (and now thirty-odd) particles was enunciated.

Quite a lot of information has been amassed on elementary particles: their properties and quantitative characteristics have been described with sufficient accuracy, they have been classified and systematized, their main transmutations are known. Nowadays scientists feel quite at home in the strange world opening up before them, they have learned to find their way about it, and things that had seemed impossible yesterday have become commonplace today. Physicists can explain complex processes and in their computations obtain results closely approximating experimental findings. Theoreticians predict the existence and a priory properties of new particles. Yet there is still no unified theory of elementary particles. More, there is no confidence that it may appear in the foreseeable future.

The task of scientific cognition is not so much accumulation of facts as discovery of the laws they represent. It is not enough to know a particle's mass, spin and charge. Much more important is to say why the electron's mass is 9×10^{-28} gram and not more or less, why there is such a thing as the muon, why the neutron is 1,838 times heavier than the electron while the pion is only 264 times heavier, why the lifetimes of particles differ so greatly, why there are only three possible charge values, $+1$, 0 and -1.

It is like Kipling's "one million Wheres, three million Hows and seven million Whys", with no apparent end in sight.

One American magazine once published a chart predicting the development of science and technology in the 20th century. It forecast the solution of many difficult problems in the coming years: animals with artificial hearts, radiotelescopic exploration of the limits of the universe and many other breathtaking achievements. But enunciation of a general theory of elementary particles was relegated to the hazy horizons of the future.

The connection between the properties on which the

classification of elementary particles is based and their behaviour in different interactions inevitably leads to the idea of a unified theory capable of deriving the properties of different classes of particles from some unified interaction process that takes different forms. The complexity of this problem lies, in the first place, in its diversity. A unified particle and field theory must be capable of deriving from a single premise the masses and charges of a large number of particles of different types, of explaining the existence of isotopic families, of theoretically describing the characteristic features of different fields, and of determining the coupling constants for various interactions.

Before speaking of the attempts to reduce the diversity of particles to a single particle let us illuminate in greater detail a problem we brushed upon in passing before. It can be defined briefly as "Establishing a Criterion of Elementariness".

Most authors of popular works on nuclear physics solve the problem fairly simply by stating that elementary particles are not at all elementary and the term should be taken in inverted commas. This is correct in a way, but incorrect in other ways. Elementary particles are certainly not all that elementary, and yet we lack sufficient grounds to claim that they are not elementary. The question is not so much one of terminology as of substance.

In an article written in the form of a dialogue between A and B, the Japanese physicist Shoichi Sakata presents the question of establishing a criterion of elementariness as a major problem of physics and philosophy. Here is a recapitulation of a portion of the argument.

A. From the point of view of materialist dialectics elementary particles must be regarded as one of the levels in the structure of matter, mustn't they?

B. Precisely. In speaking of elementary particles we must bear in mind, with so many known types of particles, they cannot, apparently, be treated as particles of matter belonging to the same levels of structure (i.e., different elementary particles are "elementary" to varying degrees—E.P.).

A. It is probably this idea that yielded the "composite" elementary particle model, isn't it?

B. Lately the structure of elementary particles has become a practical problem. Conditions have changed a lot

since the time when Yukawa enunciated his nonlocalized theory. Today, when the point model has been abandoned, the time has come to evolve a nonlocalized theory.

A. From this point of view can it be said that the claim that elementary particles represent the ultimate limit in the divisibility of matter has become an obstacle to the development of physics?

B. It would probably be wrong to say that elementary particles can be split into numerous smaller particles, but if one proceeds from the existence of a subquantum level, as postulated by Böhm and Vigier, then it must be said that their relativistic liquid drop model opens up quite a few possibilities.

A. Do they consider that elementary particles are made up of corpuscles belonging to the subquantum level of the structure of matter just as matter is made up of elementary particles?

B. One can envisage a spatial body consisting of subquantum corpuscles: then elementary particles are like the tips of icebergs rising above the surface of the sea. In "conventional" quantum theory matter and space are separated. One can detect in Böhm's ideas a close link with Einstein's relativity theory.

It seems apparent that any attempt to establish a criterion of elementariness goes far beyond the domain of terminology, and even philosophy. It is, in the first place, a question of choosing a road that could lead to the development of a unified field theory, a question of substantiating the dualism of matter and space-time. In terms of our narrow task it represents a deep probing into the subquantum world, into the microworld of the microworld.

Despite all the differences that divided the elder natural philosophers of the Ionian school, they had one thing in common which left an indelible trace in the history of physics: their concept of a primary substance capable of transmuting into all other substances (the prime source of all real things), and atoms, a product of logical reasoning, the ultimate substance of all observable phenomena responsible for all changes taking place in the sensible, perceptible world.

This concept of the immutable atom entered natural science. Without the atomic concept it is impossible to comprehend Newton's definition of mass as a measure of

the quantity of matter proportional to its density and volume.

Newton's understanding of the atom, consolidated in the subsequent development of classical physics, survived for quite a long time. Heinrich Hertz reduced different kinds of energy (electromagnetic, chemical, thermal) to the kinetic energy of invisible, homogeneous material points. Maxwell also adhered to Newtonian concepts of the atom. The new concept of chemical element that appeared in classical physics was in effect an extension of the atom concept. Even today, when a scientist is not concerned with atomic theory but only with the properties and behaviour of macroscopic bodies which must be explained in terms of the properties and behaviour of microscopic entities, he will make use of the Democritus atom principle.

But natural science and philosophy also evolved ideas opposed to atomism, ideas of the continuousness of material substance. Aristotle regarded matter as that of which things are made and out of which they appear. According to him space is completely pervaded with matter and there are no such things as void or tiny indivisible portions of matter (atoms).

Descartes utterly rejected ancient concepts of atoms and void as the basis of the universe. In his view only "infinitely divisible continuous material substance whose attribute is extension" could be the basis of all things existing.

It was some time before the Cartesian conception of the development of matter gained a foothold in physics. It required the Faraday-Maxwell theory of electromagnetism and the classical field theory for the conception to be fully, as it then seemed, substantiated.

Physics of the end of the 17th and beginning of the 18th century advanced the fatal idea that gravity could be transmitted between two bodies only by some intermediate medium. From the point of view of pure mechanism action at a distance seemed sheer nonsense. Attempts to explain gravity were undertaken by the Cartesians, who held that only touching bodies could interact.

An interesting situation arises in this connection. Reasoning strictly, we find that the idea of interaction through contact does not in essence differ from the idea of action at a distance; there is no such thing as absolute touching of atoms as otherwise they would fuse and matter would

no longer be discrete. Hence it became necessary to ascribe forces to atoms capable of preventing their fusion. As is known, physics overcame the contradiction by introducing the concept of field. But the price that had to be paid for this!

NOT ELEMENTARY AND NOT A PARTICLE

Elementary particles interact in such tiny space-time domains that physicists have no way of directly observing the nuclear events. All they can do is record the end results of interactions taking place in a world so different from the one around us. But where tools and instruments are powerless the mind is omniscent. With the facts of end results, such as a photographic plate with the fanciful tracks left by sundry charged particles, the physicist mentally delves into their invisible world, creating first abstract models and then the mathematical theory of processes. Theory is the key to nature's most sophisticated codes.

The new qualitative features of quantum laws rise like a mighty stream from the source that welled to the surface at the turn of the century: the quantum of action discovered by Planck in 1900. There is something symbolical in this. It would be hard to imagine a better beginning for our atomic and space age. What a brilliant sequel to stern and ordered beauty of classical physics.

Discovery of the discrete nature of action not only transformed physics and adjacent fields of natural science but enriched philosophy as well. The problem extends far beyond the concepts of electron levels. It has a bearing on a vast realm of things, including art, for its essence lies not so much in black-body radiation as in the nature of human cognition. That is why we are so irresistably attracted by the mysteries of matter, so deeply excited by the secrets of time and space which endlessly confront us with the question of the limits of our knowledge, of its power and weaknesses, of still unknown possibilities.

But what is this qualitative peculiarity of quantum laws and the theoretical conceptions bred by them? We have already spoken of particles which spread like waves and have no trajectories, interact at a distance and turn into light. In effect, however, we have been merely postulating their strange qualities. Now one would like to get

to the quick of things and be able to say why they are thus and not otherwise. But here we are confronted with an insuperable barrier standing between formulas and verbal descriptions. We write and speak according to the laws of common sense, which is just what the formulas describing quantum processes seem to lack.

Things are, however, not all that hopeless, and no physicist expounding theory to an inquisitive layman was ever at a loss for words, analogies and metaphors to explain his point.

Quantum theory consists of two parts: nonrelativistic quantum theory of elementary particles and relativistic mechanics. But as relativistic theory generalizes and develops the laws of nonrelativistic quantum mechanics the two are usually considered together. That is why relativistic theory cannot be grasped to the fullest without introducing the basic conclusions of quantum mechanics.

Let us examine three more or less familiar basic laws revealed by the nonrelativistic theory and see to what extent they differ from classical laws.

First, particles possess no trajectory. This is a manifestation of the relativity of such apparently definitive concepts as a particle's momentum and spatial coordinates. From this derives the division of matter into substance and field, that is, the wave-corpuscular dualism already mentioned. The quintessence of dualism is that we are simply unable to describe or, more exactly, imagine the propagation of an elementary quantum either as a particle or as a wave process. It is neither. Though some people say it is both. Be that as it may, but it is another manifestation of the great unity of opposites.

The second feature, like the first, derives from the finality of Planck's constant. It contains in itself a new quality arising from the interaction of a subatomic entity with a classical macroscopic instrument. Physical instruments are essential tools of cognition. As long as they helped us get to know the surrounding world everything was fine. But as soon as men aimed their classical macroscopic devices at the microworld a conflict of incompatibility of systems arose. It could hardly have been otherwise. By our very nature we are capable of making only macroscopic bodies. But this is no reason for us to deny ourselves knowledge of the foundations of the universe.

Nonrelativistic theory showed that we are unable to cut ourselves off completely from the observation instruments in characterizing subatomic states. A particle behaves differently in different macroscopic conditions, and its behaviour depends on the nature of the measurement.

These extremely important and as extremely difficult things can be understood only through a clear understanding of a concept known as the Ψ function. Let us not attempt to translate this essentially mathematical concept into lay language. All that need be said is that this is the wave function in Schrödinger's equation—one of the fundamental mathematical equations of the microworld—and that it characterizes the state of an individual particle.

Does this mathematical quality relate only to the results of measurement or does it characterize a particle's objective state prior to, and perhaps after, the measurement? That is the question, a truly Hamletian dilemma on which many things hinge. If we reflect on this dilemma we can see that it involves something more than quantum mechanics as such. For again there arises the question of the nature of cognition of subatomic entities according to their macroscopic manifestations. And this means that once again we must reflect on the nature of human knowledge in general.

The function concerning us does not depend on the final stage of measurement and thus represents an objective characteristic of an individual particle. This is most important: objective, i.e., independent of our desires and our instruments. But at the same time the function characterizes the peculiar features of interactions between micro- and macrobodies, defining the probability of this or that measurement. It is useless to judge, say, of the distribution of particles by momentum and coordinates before a measurement. Both these concepts taken together are incapable of describing the behaviour of inhabitants of the microworld. But this is only one point of view. There is another, based on the assumption that the wave function refers only to the results of measurement and therefore it is meaningless to judge of a particle's objective state before the measurement.

Opposites often meet and, whether they like it or not, the exponents of the two interpretations of the wave function also meet on common ground. The thing is that neither the former nor the latter interpretation is fully consis-

tent. The truth lies somewhere in between. It rises above the extremes as a new quality in a new revolutionary leap.

The third feature of quantum processes is linked with the probability laws, the basis of the microworld. A separate particle may possess a whole spectrum of momentum and coordinate values. There are no analogues of this in the macroscopic world, and in terms of classical concepts atomic phenomena can be described only statistically. As for the law of causality, in the microworld it simply cannot be defined in terms of classical concepts. Wave functions are the medium for this.

To sum up, it can be said that quantum-mechanical description successfully solves all the contradictions between the quantized nature of particles and classical conceptions of space and time.

Now let us see what new qualities are introduced into the basic features of nonrelativistic theory by its further development and generalization over the domain of high (relativistic) energies. In short, let us examine the basic features of the relativistic theory.

The relativistic theory's purpose is to explain the existence and transmutations of all elementary particles. The breeding and reciprocal transmutations of particles and the close interconnections between interaction characteristics is in essence the new quality inherent in the relativistic theory. Its mathematical apparatus must be a catalyst capable of effecting the long-awaited synthesis of relativistic and quantum concepts. The task is to effect a harmonious joining of equations including the velocity of light c with those including Planck's constant.

The trouble is, in the words of Prof. V. Ya. Feinberg, "that today there is no such theory. To be more exact, however, it originated long ago (in the 30s), is continuously developing and, in spite of all (perhaps only apparent?) internal contradictions must inevitably lead to the creation of a consistent relativistic quantum theory of elementary particles."

It is a difficult situation. As soon as we start speaking of quantum mechanics we run into contradictions. On the one hand, there is no theory, on the other, it originated a long time ago and is developing successfully. Moreover, it studies extremely strange entities possessing truly incomp-

rehensible properties. So that we hardly know whether it exists in flesh and blood or only as an apparition.

Today there are two basic approaches to the problems facing the relativistic theory. Both, to be sure, proceed from given charges, masses and spins of known elementary particles, but it is to be hoped that this restriction will soon be overcome. It is not easy to describe the essence of the approaches to the solutions of problems of relativistic mechanics. It is impossible to sidestep such concepts as secondarily quantized probability amplitude (first approach) or S-matrix method (second, axiomatic approach). Therefore it is more appropriate to speak, not of the essence of these beautiful mathematical equations, but of their use. Every new attempt to resolve the contradictions gives prominence to certain characteristic features of "true" relativistic theory and is applicable only in a very restricted domain. But it is these precious bits of "trueness" that help us attain the absolute truth. Drop by drop, spangle by spangle, and the glittering contours of the new theory begin to come out of the mist.

Today we can say that, whatever its shortcomings, a relativistic theory of elementary particles does exist. The two approaches, a description of which we so cunningly evaded, as yet yield no qualitative discrepancies between prediction and experiment.

Let us examine the basic traits of the relativistic theory which make it so different from what has by now become the classical nonrelativistic theory. These traits are not associated with any specific mathematical formulation and in one way or another derive from the nonconservation of the number and nature of particles as a result of their interactions.

Relativistic theory reveals the deeper relativity of classical concepts and additionally restricts the domains of their application. Not only is it more radical than the nonrelativistic theory, it also reveals the relative nature of many of its fundamental concepts. The interactions of relativistic particles can no longer be described by a wave function for a given number of entities, and in the realm of high energies this function simply loses meaning—together with the arguments raging around it. High energies mean, in the first place, tiny distances and negligible time intervals, a world of different laws and different spatio-

temporal forms. They provide the key to a subatomic world much more refined than the atomic world of nonrelativistic mechanics.

Most important, the relativistic theory provides natural, exhaustive explanations of the most specific quantum properties. Essentially, the last differences between classical field and quantum particle disappear, revealing a profound inner unity between them. Any opposition of matter to field becomes meaningless.

In relativistic theory a particle is an excitation quantum of the corresponding field. Moreover, the very concepts "particle" and "field" merge into a unified "quantum field". Interactions of different quantum fields cause quantum particles to scatter, breed or transmute into other quantum particles.

As we shall see later on, the dialectics of the concept "elementary particle" bodies forth vividly when such properties as the point nature of particle interaction and structure are investigated. Relativistic theory gives these concepts a concrete, graphic meaning. Thus, in particular, even a single particle taken all by itself cannot be localized in a spatial domain $\lesssim \left(\frac{h}{mc}\right)^3$ where m is the particle's mass. That is why, even in the absence of interactions, the concept of a point particle is meaningless. The departure from self-evidence, begun when the first laws of the quantum world were postulated, continues. Not only have elementary particles ceased to be elementary in the narrow sense of the word, they have even ceased to be particles! And if we say that an elementary particle is neither corpuscle nor wave, so we can say with equal justification that it is neither elementary nor particle.

When interactions are taken into account particles acquire spatio-temporal structure. In relativistic, as in nonrelativistic theory when noninteracting particles are considered, they are characterized by mass, charge, spin, etc., but not internal structure; it is only in interactions that the profound difference between the two theories becomes apparent. In relativistic theory the concept of structure is inseparable from interaction. To put it otherwise, structure displays itself only in reactions between particles. It is meaningless to speak of the structure of a particle taken in isolation. Should a particle take it into its head

to walk by itself, like Kipling's Cat, relativistic theory would simply declare it nonexistent.

Relativistic theory offers a deeper insight into the interaction between the state of a subatomic entity and a macroscopic instrument. This is the domain where the relative nature of observation becomes grossly apparent, as expressed, for example, by the fact that in one case an electron may possess only a definite momentum and in another only a definite set of coordinates. In nonrelativistic mechanics one can speak of an electron's coordinates and momentum only after the instrument involved in the measurement has interacted with the particle. Thus the contradiction is resolved at its very foundation. A brilliant example of the spiral development of theory.

Finally, the third feature of relativistic theory is that the concept of probability becomes increasingly important. The further quantum theory is developed the more consistently must classical notions be rejected in application to small spatio-temporal domains. There is an analogy here with the modern specialization of scientific professions, with the result that a researcher gets to know more and more about less and less. As Bernard Shaw put it, if this goes on the day will soon come when we shall be knowing everything about nothing.

WHAT IS "ELEMENTARY"?

The development of atomistics, the ideas of which pass through the whole history of natural science, was not restricted to the search for a substance which could be declared the ultimate substratum of all observable phenomena. The question of the criterion of "elementariness" which has been raised would appear to be relatively new, although in one form or another it can be traced to many thinkers of bygone ages. Let us take the position of Sakata's A and B and attack the particles directly.

By now we know that some particles are stable while others undergo various transformations. We shall begin by rejecting the thought that seems to suggest itself, namely that the stable particles, the photon, electron, proton, neutrino, can be treated as truly elementary on the basis that they do not disintegrate spontaneously.

This brings us back to the idea expressed before that

a spontaneously decaying particle, a neutron, for example, does not comprise the decay products. In the same way, if one particle breeds or absorbs another in certain conditions we cannot on this basis claim that the former is "in reality" complex while the latter is "in reality" elementary. All we can do is repeat Igor Tamm's words that, though there exist a number of schemes attempting to select a small number of truly elementary particles and use them to build up all the others, there is still no unique solution to the problem.

After these reservations all that is left for us is to define as an elementary particle any entity that does not comprise other particles. Which is to say that an elementary particle is an ... elementary particle.

Is there any better definition? At first glance it appears that there may be several subdivisions of matter in which each stage can be regarded as either complex or elementary, depending on specific conditions. Such hierarchic systems have frequently been employed in natural science. Newton's conception also embodied the idea of an hierarchy of particles of increasing degrees of complexity with "the smallest portions of natural bodies" at the base. Scientists speaking today of the levels of structure of matter adhere to the same conception: elementary particle level, nuclear and atomic level, molecular level, cellular level, etc. The classification can be extended into the macroworld and megaworld and, quite feasibly, into the mircroworld. Nowadays it is common adage that the "indivisible" atom and atomic nucleus are only relatively elementary, in comparison with more complex stages in the fragmentation of matter. Perhaps the same element of relativity is present in elementary particles?

The known interactions of elementary particles result not in their fragmentation but in the creation of other elementary particles. To be sure, new and more powerful tools capable of forcing particles closer together than ever before may help us pass the threshold of elementariness known today and yield subelementary entities. More, we can well assume that there is no end to the possible divisions of matter, that it is infinite on both the "elementary" and "complex" sides. This assumption does not contradict known physical data. Still, exciting as such forecasts might seem, they are no more than intellectual guesswork and

not very original attempts to predict the results of as yet uncontemplated experiments. Does the problem of elementariness have any other solution? M. E. Omelyanovsky sees the key to it in the relative nature of the concepts of elementary and complex.

First, let us see if we are not confusing such concepts as "complex" and "composite". Instead of claiming that the two words are synonymous we had better remember that in the microworld we must abandon the commonplace and self-evident. "Complex" in the meaning of "composite" derives from notions bred by centuries of observations of macroscopic phenomena. Steppe is seen as a multitude of plants, sea is a myriad of drops, etc. In some circumstances this understanding of "complex" is doubtlessly valid. It was applied to questions connected with the structure of matter, when it bred the concept of "structure" as an arrangement of separate particles. But is it applicable to problems put forth by the theory of elementary particles? Can we approach them with old, habitual yardsticks?

No, we cannot.

In fact we can't even employ such habitual concepts as "complex" or "elementary" in their literal sense. Similarly, other concepts also lose their conventional meaning, such as "comprise" or "consist" (in the sense of being compounded of elementary or simpler things).

Already in nuclear physics the notions of elementary and complex are partially stripped of their initial abstract character. When we say that an atom of hydrogen comprises a proton and electron the idea conveyed by the word "comprises" is not the same as in the assertion that a necklace comprises beads. There is no difference between a bead taken separately or within the "necklace system", but a free proton and an electron differ in many ways from the proton and electron in a hydrogen atom. The mass of the atom is less than the combined mass of the proton and electron. Similarly, an atomic nucleus is not simply "compounded" of protons and neutrons. Suffice it to say that a free neutron decays spontaneously whereas in the nucleus it is stable.

Nor can we accept the concept of mass defect as a criterion of elementariness. And here is why. In the case when the mass defect in the formation of a system is less than the masses of the component parts we could, evidently,

say that the system "comprises" these particles. Any schoolteacher will tell you that a nucleus comprises protons and neutrons. And yet this is wrong. It is with some reservations that we can declare that a pion, for example, comprises a nucleon and antinucleon, as practically the whole mass of the two nucleons is reduced to naught by the mass defect, leaving only a tiny portion as the pion's mass.

On the other hand, we seem to have grounds for claiming that a nucleon field is more elementary than a meson field since the latter is produced from the former. Furthermore, bosons are complex combinations of fermions. And yet we cannot say that bosons comprise fermions on the sole grounds that fermions transmute into bosons.

As applied to elementary particles the concepts "elementary" and "complex" acquire an entirely different meaning than in classical atomistics. Here the basic concept is that of "transmutation". But classical atomistics regarded transmutation as a result of the joining and separation of certain constant elements, which is quite inapplicable to the world of quantum.

From this stems an entirely new approach to the principle of the unity of matter. The discovery that the atom is divisible was a tremendous step forward toward man's understanding of the unity of matter. "Instead of dozens of elements, consequently," V. I. Lenin wrote in this connection, "it is possible to reduce the physical world to two or three ... Consequently, natural science leads up to the 'unity of matter'."

The reciprocal transmutability of elementary particles was a new quality that presented itself to scientists in their quest for the unity of the world. Elementary particles are not immutable atoms in the spirit of Democritus and the atomists of the past. Modern physics has as it were built a bridge from the principle of the evolution of matter to the principle of its unity. The reciprocal transmutability of elementary particles is convincing proof of the unity of matter at its very foundations.

It is time now to return to the question: Are elementary particles elementary or not? Yes or no?

After our digressions into philosophy and the history of natural science one may rightfully challenge the legitimacy of such a direct question.

When we speak of elementary particles terms like "ele-

mentariness" or "complexity" acquire a different meaning than in classical atomistics. In the microworld they cease to be definite, become nebulous and interrelated and acquire new meaning.

We call a proton an elementary particle, but we have seen its complex structure: it has a core, a shell, and can change into other particles. Is the proton elementary or complex? Neither—or both, for it simultaneously possesses qualities of an elementary and a complex entity.

The same can be said of other particles. The proton is elementary or complex only in relation to the circumstances of its transmutation. These circumstances are specific and can be registered by instruments. In experimental conditions at energies below 100 MeV it behaves like an elementary particle; in collisions with particles of much higher energy "breaks" into hyperons and K mesons, thereby displaying properties of a complex particle. Thus the concepts "elementary" and "complex" stop being absolute and become relative instead.

Everything seems so simple: in the macroscopic world "elementary" and "complex" are absolute notions, in the microworld they are relative. But if that is the case then one must postulate this as a special property of the microworld. This is not done, however, and here is why.

Elementary particles are, of themselves, neither elementary nor complex. They manifest themselves in one of these qualities when limiting cases are considered only in connection with the conditions in which the transmutations take place.

Without fear of repetitions, we can say that by themselves the particles simply lack the properties ascribed to them. But as soon as we begin to consider interactions of particles their properties are manifest. Elementary particles are endowed with elementary-complex duality, a peculiar quality which defies qualitative comparison with anything. This is the unity of opposites noted by ancient sages hundreds of years before Hegel.

The question of the elementariness or complexity of entities is in some ways similar to that of the identity of place of two events separated in time or the simultaneity of events occurring in different places. Classical mechanics assumes that place unity is relative while simultaneity is absolute irrespective of the frame of reference. Rela-

tivistic mechanics rejects the idea of absolute simultaneity. The relativity of simultaneity, like the relativity of spatial and temporal intervals in Einstein's theory, derives, as we know, from a recognition of the inner unity of space and time. Where the ancient sages added to the endless lists of "mysteries of duality" such concepts as birth and death, addition and subtraction, etc., modern science deals with the fundamental "dualities" of the universe: space-time, elementariness-complexity.

Just as the concepts of elementariness and complexity in their classical sense are inapplicable to elementary particles, so is the classical understanding of structure inapplicable to them. The proton's structure, for example, involves several shells of virtual particles: nucleons and antinucleons, hyperons and K mesons and, of course, pions. Every elementary particle is surrounded by a system of shells of virtual particles. But as a given elementary particle is made up not of real but of virtual representatives of the microworld the concept of "structure" cannot be taken in its classical sense.

A. L. Zelmanov distinguishes three concepts of the universe: "the whole universe", "the universe as a whole", and "the entire universe". The first concept denotes the whole without reference to its parts; the second denotes the whole with reference to the whole; the third denotes the parts without reference to the whole. "Confusing these concepts," Zelmanov writes, "can lead to serious misunderstandings." This understanding of the correlation between the whole and its parts can be extended to any object regarded as a whole. The concept of elementary particle, for example, is analogous to the second concept from the point of view of the connection of the whole and the parts as expressed by the relationships of the complex and the elementary, the continuous and the discontinuous. The whole is not just a simple arithmetical sum of its parts. It represents a dialectical unity with them.

IDEAS OF NATURAL PHILOSOPHERS IN TERMS OF TENSORS AND MATRICES

In the spring of 1942 Albert Einstein wrote to his friend Dr. Hans Mühsam.

"I am an old man known mainly as a crank who doesn't

like to wear socks. But I am working more fanatically than ever and still hope to solve what has become for me the old problem of the unified physical field. It is like being high up in the sky in a flying machine with a rather vague idea of how you will ever get back to the ground ... perhaps I will still live to see better times and catch a fleeting glimpse of something of a promised land."

Einstein continued to work on the unified field theory till the end of his days. In 1959, Heisenberg wrote a paper, "Remarks on Einstein's Outline of the Unified Field Theory", in which he analysed the reasons for Einstein's failure.

Why did the brilliant, ordered theory prove invalid? First of all, because it was premature. Einstein worked on it at a time when practically every month physical journals carried news of the discovery of a new elementary particle, and every such particle was associated with one field or another. It was difficult, if not impossible, to find a solid basis for a unified theory in the sweeping avalanche of new facts.

"The essentially remarkable attempt," Heisenberg writes, "at first seemed to fail. At the very time when Einstein was working on the unified field problem new elementary particles were being discovered in endless succession, followed by new fields correlated with them. Owing to this there was no solid empirical ground for the implementation of Einstein's programme, and his attempt failed to yield convincing results."

But is that really the case?

Dircoveries of the last decades have introduced to the world picture transmutable particles and correspondingly transmutable fields. The unified field theory now has a basis: quantum concepts. The reciprocal change of one field into another is a reciprocal changeover of field quantum, a transmutation of elementary particles. The idea of a subquantized world of ultrarelativistic effects and the unified field theory blend into an integrated conception of mutual transmutations of elementary particles as the fundamental processes of the universe

Actually there is still no such conception, and all one can speak of is the possibility, in principle, of eventually producing a world picture in which the fundamental concept is the motion of a particle identical to itself in some

field or other, a world picture in which the fundamental element will be the transmutation of one particle into another.

The unified field theory, when it is enunciated, will be more than the embodiment of a great physicist's ideas, more than their development. It will conclude the theory of relativity with which the 20th century began.

There have been quite a few attempts to reduce the diversity of particles to a single particle. One of the most notable was Louis de Broglie's fusion theory.

This theory is based on spin. The unified field quanta, called **elementons,** are all identical and possess spin. This follows logically from the fact that all elementary particles possess spin, which cannot disappear. What should the elementon's spin be? Obviously not zero, for no matter how one combines nonspinning particles one can't produce a spinning one. Unity spin, apparently, is also unacceptable since no combination of integers can yield one-half. Thus the only possible value is $\frac{1}{2}$ and, accordingly, the elementon, like the neutrino, electron and positron, is governed by the Fermi statistics and described by a peculiar mathematical quantity typical of fermions and called spinor. And the field produced by elementons is a spinor field.

Since all other particles can be "made up" of fermions, de Broglie regards them as the genuinely elementary ones. The wave functions of other particles should be represented as products of the neutrino, electron and/or positron wave functions. According to this view the photon is made up of two neutrinos.

In some models other particles are also regarded as the results of fusions: pions are made up of nucleons and antinucleons, the notion is introduced of nucleons and heavy mesons and nucleons and hyperons as of primary elementary particles.

M. A. Markov's theory of hyperons as "excited states" of nucleons is linked with the conception of "internal statistical space". Paradoxical as it may seem, Markov considers the photon, which has no rest mass, as a combination of heavy particles: proton and antiproton, neutron and antineutron. The electrical charges of the former pair are neutral and the whole system therefore also has zero charge, while the titanic nuclear forces produce such powerful

mutual attraction that the mass defect becomes equal to the sum of the masses of the individual particles.

The Soviet scientist holds that not only the photon but any other particle can be represented as a combination of particles and antiparticles. Nuclear forces make matter and antimatter fuse together, tucking the antiworld away inside matter itself!

And what about spin? The photon has unity spin, hence for the half-integral nucleon spins to yield unity there must be an even number of them. But why four and not two or six to make up a photon?

Markov considers this system to be the most stable.

The zero spin of the neutral pion, on the other hand, is composed of the spins of two particles, a nucleon and antinucleon, which are known to be antiparallel. This is an unstable system, and as is known the pion decays quickly. The half-integral spins of fermions are also due to combinations of different numbers of nucleons, an odd number in this case. But what about hyperons, whose mass exceeds that of nucleons? Markov sees them as combinations of nucleons and pions bound together by special forces characterizing excited nucleon states.

As we have seen, elementons must be fermions, hence Dirac's famous equation for particles with half-integral spins is taken as the basis for unified theories of elementary particles. Attempts have been made to use the equation to compute the mass spectrum and other fundamental properties of elementary particles which would yield a unified theory of excited states of a universal spinor field. But excited states can also be the result of interactions between fields. And if there is only one field its excited states are manifestations of its "self-action", i.e., its interaction with itself.

The ability to interact only with itself is an important property of the unified field, and it was not invented by latter-day theoreticians. It is a property the ancient natural philosophers had ascribed to their primary matter, which is only natural as any primary matter is by definition the sole cause and essence of all things and phenomena in the world.

The unified spinor field's "self-action" means that the differential equation describing it must be nonlinear, as the wave function must enter it raised to some power.

In 1939, D. D. Ivanenko developed a nonlinear spinor equation in which to Dirac's equation is added a simple nonlinear member in the shape of a wave function raised to the third power with a factor corresponding to the intensity of the spinor field's "self-action".

On 25 February 1958, Werner Heisenberg, creator of the fundamental equation of quantum mechanics, gave a lecture at Goettingen University on the subject "Progress in the Theory of Elementary Particles". He reported that he and his associates had succeeded in producing an "integrated nonlinear spinor field theory". What is the essence of this most interesting theory of recent years?

Frankly speaking, this is not an easy question to answer. For one, we shall be speaking of mathematical relationships without actually invoking them. Without presenting Dirac's equation or showing how Heisenberg generalized it we shall be speaking of going over from the former to Heisenberg's. Moreover, in speaking of mathematical operations with the equations of quantum mechanics we are compelled, as far as possible, to evade terms such as "negative probability" or "secondary Hilbert Space".

The task is an extremely difficult one, if at all feasible. One could ask, of course, why we can't resort to visual examples and with the help of analogues show, at least to some approximation, what the transformation of Dirac's formula has led to and what the new theory offers.

The thing is, unfortunately, that in the present case there are simply no visual analogues. Our notions and conceptions, the very nature of human mentality as shaped over the ages, are incapable of graphically imagining or embracing the essence of the processes involved. Besides, who said that the laws of nature must necessarily fit within the Procrustean boundaries of visual schemes? Especially as we have already seen on the example of atomic nuclei and elementary particles that visual analogues are poor substitutes for real things. That is one of the reasons why mathematics is making such great inroads into natural science.

That is why, in developing the unified field theory, in Heisenberg's words, nature must be asked questions in mathematical language as the only language in which we can obtain an answer; the question itself, however, is directed at a process taking place in the practical material world.

Heisenberg's fundamental physical idea has much in common with the views of Pythagoras and Aristotle and consists in a recognition of the eternal form of all types of matter, of uniform primary matter. This primary matter is the unified physical field. and it simultaneously possesses the properties of discreteness and continuousness.

Being continuous, the unified field embraces the whole of the universe, all forms of existence of matter: galaxies and particles, fields and stars. The unified field's discreteness characterizes its quantum properties: the primary matter is made up of indivisible elements.

In his work Heisenberg proceeded from two stumbling blocks in the field theory of elementary particles: firstly, the appearance of diverging mathematical expressions in bringing relativity theory and quantum theory together; secondly, the empirical nature of the values of mass, charge and other elementary particle characteristics. To this can also be added the absence of an objective criterion of elementariness.

From here stem the requirements the unified field theory must satisfy: (1) the field operators in the equation must refer not to a specific particle but to matter as a whole; (2) particles must correlate with the proper solutions of the field equation; (3) the equations must take interactions into account, i.e., they must be nonlinear, the mass of particles must derive as a consequence of their interactions, and the concept of a "bare particle", a particle in itself, cannot have meaning; (4) particle production and decay are computed by selection deriving from the symmetry of the equations; (5) provided the selection rules and invariance requirements are satisfied, the heuristic principle is the equations' simplicity.

Translated into a simpler language, it follows from these requirements that the unified field must be capable of self-excitation. This is essential for the primary matter to be capable of producing an elementary particle. And different particles will correspond to different excitation states, or, in other words, every particle corresponds to a certain degree of excitation. Now we can quantize the unified field and determine the smallest "portion" of the primary matter, the "building block" out of which everything is made: the elementon.

The primary matter can interact only with itself. There is nothing but the primary matter, and all that surrounds us—gases and liquids, crystals and plasma, stars, atoms and particles—are but manifestations of the basic field. This field must be capable of self-excitation. For if it remained at rest all we would have would be the "building block", the elementon with spin $\frac{1}{2}$. And nothing else.

The five conditions the new theory had to satisfy combined to present an extremely complex problem. It was therefore expedient to start out with investigating a simplified model. For such a model was taken the nonlinear equation of the spinor wave function, which to a degree meets the requirements.

Instead of the empirical value of mass Heisenberg computed it by solving a field equation which included, along with Planck's constant and the speed of light, another world constant, the minimum length $l_0=10^{-13}$ cm, a measure of the "self-action" of the world spinor. Quantization of the equation yields a series of excited states of the spinor corresponding to the mass spectra of different particles. The results agreed with empirical values. Thus, Heisenberg obtained the correct relationship between the masses of a nucleon and a pion.

If there were no interactions there would be no particles, to say nothing of their masses. Hence, the initial element in the world picture is not a particle, with its constant proper mass, but the excitation of the field due to its "self-action".

Heisenberg's new world constant, the elementary length, is a factor by which all proper mass values are multiplied. One can visualize particles with different mass occupying the same spatial volume and possessing the same extension.

It should be noted that there are many other works besides Heisenberg's attempting to develop a new theory on the basis of a radical revision of spatial and temporal concepts and their application to infinitesimal dimensions.

Already L. I. Mendelshtam emphasized that on this scale the notions of distance measured by a ruler and time measured by a clock are inapplicable.

The idea of indivisible portions of space and time da-

tes back into the remote past. It was voiced repeatedly by ancient and medieval philosophers.

At the end of the 19th century Stoney expressed the idea of minimal spatial distances (10^{-35} cm) and minimal time intervals (3×10^{-45} sec). Fifty years later V. A. Ambartsumyan and D. D. Ivanenko postulated that in the world of quantum coordinates expressed in terms of the elementary unit—the minimal length—could assume only integral values.

Immediately following this Heisenberg published a paper which dealt with minimal spatial domains and minimal distances. He considered that the elementary length would provide the basis for limiting quantum mechanics, just as Planck's constant limits classical mechanics, an idea which has won many adherents among theoreticians.

Later, as we shall see, Snyder and Koish arrived at the conclusion that in infinitesimal domains space is not continuous, as we imagine it to be, but discrete, i.e., consisting of separate, clearly defined points or elementary cells. The space within such a cell may be infinitely divisible, but there is no real physical process that corresponds to this divisibility. We can imagine a distance less than 10^{-13} cm and a time interval smaller than 10^{-24} sec (the elementary duration), but there are no physically different domains or time intervals that would correspond to these scales.

In this case the physical constants of length, with an order of magnitude of 10^{-17} cm, which characterizes weak interactions, and 10^{-38} cm, which represents the gravitational interaction, must be considered as conventional quantities, not characteristics of real domains in which the mentioned interactions take place.

It has been suggested that it is neither space as a neutral background of physical processes nor time as such that are discrete, but the unified spatio-temporal world, which is composed of cells in which space and time lose their relativistic connection and become independent.

Let us take a closer look at the principal works on quantized space and time. The fundamental work is Snyder's paper published in 1947. His premise is that spatial coordinates can take only discrete values: x, y, $z = \pm l_0$; $\pm 2l_0$, etc., where l_0 is an elementary length of which none can be smaller.

We know from quantum mechanics that there exist physical quantities which cannot be measured simultaneously with absolute precision. Spatial coordinates are not one of them, but mentally we can assume that x, y, z correlate to each other in the same way as the coordinates and momentums in Heisenberg's equation. Only in this case we replace h with the elementary length l_0.

If we assume that space is infinitely divisible, i.e., that $l_0=0$, we obtain the conventional theory, the habitual metrics of the world.

Snyder, however, assumes $l_0=\text{const}$, and from this far-reaching conclusions follow. According to relativity theory time and spatial coordinates enter all formulas symmetrically; thus, although the coordinates are discrete, time acquires a continuous spectrum of values. In other words, in this case time is not quantized.

The physical meaning of the theory is that it is impossible to measure all three coordinates of a particle simultaneously and exactly. Exact measurement of z, for example, prevents the exact measurement of x and y. It follows from this that it is impossible to localize a particle in space.

For almost two decades Snyder's idea stood like a lone island in a boundless sea. Only comparatively recently was it developed in the works of Soviet researchers Yu. A. Gelfand and V. G. Kadyshevsky.

Even more radical than the hypothesis of discrete space was the theory of finite space-time enunciated in 1959 by Koish. Here is how the Soviet physicist I. S. Shapiro defines it:

"According to this, at first glance, utterly 'mad' conception, in the microworld space and time are described by not merely a discrete, but a **finite** set (which, in particular, means that space comprises a great, but nonetheless **finite**, number of points)."

We shall return to the problem of infinity later on. At present we shall restrict ourselves to the most general conclusions of Koish's theory. In it there is simply no such thing as infinity, while the very fact of the finality of the number of points gives rise to an avalanche of new and remarkable properties of space-time symmetry. Most important, the symmetry properties of elementary particles deduced from the theory agree well with experimental data. This is a major success indicating that the theory perhaps

reaches down to some of the most basic properties of the world system.

In general, the fundamental properties of space are responsible for some physical laws even within the habitual framework of localized theories. The classical laws of conservation of energy and momentum derive directly from the homogeneity of space and time. More specifically these laws are conditioned by the fact that the internal properties of physical entities do not change in their displacement from one point to another and that physical laws remain constant in time.

But the physics of elementary particles has symmetry properties and conservation laws of its own which cannot be explained in terms of the symmetry of the habitual space-time continuum. There is no way of linking with space and time the fact that all electron charges are integers, or the existence and conservation of baryon charge, on which the stability of the material world is based. The same is true of the law of conservation of lepton charge and many other features governing the strange world of elementary particles.

Both Koish and Shapiro showed that all symmetry properties are easily explained theoretically as corollaries of the finality of space. More, the equations deducible from this theoretical premise acquire precisely the form required by relativity theory. This is a fact of extreme importance. For it means that in principle the theory can be extended from the microworld to the whole of the universe.

And one more interesting, or rather paradoxical, feature of the Koish-Shapiro theory: in the microworld the concept of length, i.e., distance between two points, loses all meaning. This is both remarkable and attractive as it automatically removes many theoretical difficulties. Moreover, we can get used to this hypothetical peculiarity of the microworld just as we got used to the idea that elementary particles move without trajectories.

It was Riemann who wrote, "The question of whether the assumptions of geometry are valid in infinitely small domains is closely related to the internal cause of metric relationships in space. This question, of course, also belongs to the teaching of space and in investigating it one should bear in mind the remark made before that, in the case of discrete sets, the principle of metric relationships

is contained in the very concept of this set, whereas in the case of a continuous set it must be sought elsewhere. It follows from this that either the reality that breeds the idea of space forms a discrete set or one must explain the appearance of metric relationships by something extraneous, by the binding forces acting on this reality."

The idea expressed in the concluding words of this classically precise formula was embodied in the general theory of relativity.

Investigations into this radical concept of finite space are only just beginning. It is hard to predict how fruitful they will be, but the spirit of contemporary theoretical physics enables us to claim confidently that what is unusual is by no means impossible.

More, only radical ideas are capable of throwing bridges over the chasms of the unknown. Traditional conceptions only serve to consolidate newly erected structure.

But let us return to the elementary length and make a brief digression from the problem that interests us. First of all, we shall speak no more of quantized space and time and, secondly, the digression on which we are venturing is important not only in itself but also because it contains some unexpected information concerning the possible development of theoretical physics.

It is perhaps significant that the two world constants which became the basis of all transformations in the atomic domain, the speed of light, c, and Planck's constant, h, were discovered at the turn of the century. Neither is specifically related to mass, length or time, though they are both composites of the basic units. The dimensionality of c is cm/sec, of h, g $\cdot$ cm $\cdot$ cm/sec. To employ an analogy, one could say that we have three unknown quantities but only two equations. A third equation, a third world constant, is thus essential. A third natural unit of measurement would provide a basis for developing a system of units as complete as the gram-centimetre-second system, and much more satisfying. Or, more exactly, much more natural and fundamental. The need for such a system will be realized from the following reasoning: if the speed of light is accepted as the unit of velocity the question of the velocity of propagation of light loses meaning. All one can say then is that light propagates as it propagates. Insofar as any measurement is no more than a comparison, a given standard should

be comparable with nothing but itself. With such a set of standards one can envisage a "dimensionless physics". Having established the velocity standard, one can say that a rocket travels at a speed of 10^{-6}, that is, one-millionth the velocity of light. The quantity 10^{-6} is dimensionless and requires no reference to any units as it is the ratio of the rocket's velocity to the speed of light. For dimensionless physics to become a reality one more independent natural unit is needed. When and if it is found it will most likely turn out to be the unit of length.

Many theoreticians consider that such an elementary unit of length will reflect some new fundamental concepts of space-time on the atomic scale.

PARTICLES AS CURVED SPACE?

Zwicky established that at a distance of five million light-years (5×10^{24} cm) gravitational forces decrease to a negligible fraction of the value provided for by Newton's law. At such distances worlds cease to exert any appreciable influence on one another and sail along through the bottomless voids of space.

In the elementary cell the great dual unity of space and time breaks down. These are the frontiers of man's present-day knowledge; on both sides lies the Unknown, the goals for future generations to pursue.

The farther their quests advance from special questions to the general picture of the universe the closer will they come to solving the most fundamental problems concerning all mankind.

It is worth noting that general concepts breaking with old notions most paradoxically have also proved to be the shortest and truest ways toward knowledge of the secrets of the universe.

"The theoretical foundations for far-reaching changes in human life," writes B. G. Kuznetsov in his excellent biography of Einstein, "are provided by conceptions lying far beyond the sphere of direct observation, conceptions involving velocities approaching that of light and spatial domains of millions of light-years and thrillionths of a centimetre, and revealing completely paradoxical (from the point of view of classical science) relationships."

Today the break with self-evidence must be even more radical than in the first half of the century.

That is why, when, in 1958, Pauli was reporting Heisenberg's theory in the United States, Bohr, who was present, exclaimed, "This is undoubtedly a mad idea. The only thing is whether it is mad enough to be true."

The point here is not so much that Heisenberg's equation, his "formula describing the world" is not perfect enough and the theory itself should be regarded as a programme for future research. The main thing is its "madness". The ideas of the future must be radical, paradoxical, "mad", they must break with tradition. We are at the threshold of an even more decisive rejection of classical fundamentals than that which a quarter of a century ago marked the beginning of present-day concepts of matter, field, space and time.

Undoubtedly deserving attention in this connection is the attempt to approach elementary particles as manifestations of the properties of space.

We have been witnesses of many attempts to offer a theoretical explanation of the "mass spectra" of elementary particles. But we still do not know why heavy particles are 3,000 times heavier than the electron nor why the muon exists at all. As long as these and other such questions remain unanswered physicists will continue their stubborn search for the most general properties and characteristics which could be used to explain the observed differences between the masses of particles.

Physicists have grown used to the great dualisms of our time. Particle-wave, space-time: these are no longer things that cause people to wonder. But perhaps there exists a dualism of a higher order? Perhaps we could write down: mass-energy-space-time? Could not this be a generalized formula of the basic components of the world?

The well-known physicist Wheeler once expressed the idea that elementary particles are curves in spatial domain which characterize their "size". The idea is profound, original and yet in a way trivial. It as it were derives from the concept of quantized space and time. At its roots the world may turn out to be remarkably uniform. If the habitual concepts of space, time, matter and field disappear we may well venture to voice the heretical idea of some

intrinsic unity of such concepts. It would then be legitimate to regard particles as space warps and extend spatial metrics to them. Many questions would automatically disappear. Why, for example, are some particles prohibited from transmuting into others? We can "forget" all the prohibitions and conservation laws by assuming that to every particle corresponds a surface of individual topological connectivity. A sphere, for example, can be turned into an ellipsoid by a process of continuous deformation as the two figures of the same topological connectivity. A sphere cannot be turned into a torus, because of their different topological connectivity.

On the whole the idea is clear, but it offers only a qualitative criterion. It remains to find a quantitative explanation of mass spectra on the basis of topological connectivity.

Such an attempt was undertaken by a Soviet physicist I. G. Ivanter. Every topological structure that possesses symmetry can be described in terms of a quantitative characteristic called the packing factor. If a certain topological structure can be ascribed to an elementary particle it thereby acquires a certain packing factor.

Thus, an electron is associated with spherical symmetry, a pion, with toroidal, K mesons and hyperons, with higher types of axial-helical symmetry. These topological structures as it were describe the curvatures of spatial metrics corresponding to the specific particles.

Note one fine point. As we know from the general theory of relativity, the curvature of spatial metrics is associated with gravitational field. Accordingly, Ivanter introduced the gravitational constant into his formula. This unexpectedly gave rise to a far-reaching corollary.

Insofar as the structures are characterized by gravitational field, when critical values of the field are approached one can expect the "deformation" and even as it were "destruction" of elementary particles. Say, the law of conservation of baryon number may fall. (It is this law that prevents mass from turning completely into energy in thermonuclear synthesis.) Later on we shall look into processes taking place when stars explode, hypotheses of the origin of the universe, and gravitational collapse, which compresses distant superstars. There are no such processes on earth. The tremendous release of energy in super dense systems

may involve the violation of some known physical laws. This is a new quality which it is hard to predict.

In any case, the first steps of the new theory purporting to explain the mass spectra of particles lead to some paradoxical conclusions. But such is the very nature of knowledge that a new discovery in the microworld is inevitably reflected in the world of galaxies and stars.

American physicists Goldhaber and Cowan measured the lifetime of protons. The precision of the experiments was such as to detect the decay of one particle in 10^{30}. The proton's stability proved so tremendous that its half-life cannot even be estimated accurately. In any case it exceeds 10^{22} years, which is ten orders of magnitude more than the lifetime of the universe.

The proton thus lives 10^{43} times longer than unstable particles with a comparable rest mass and 10^{26} times longer than the neutron. It has beaten all longevity records. The half-life of the electron, measured several years ago, proved to be "only" 10^{17} years—and this is, for all practical purposes, eternal.

If not for this remarkable stability of the electron and proton we would probably never have been able to study elementary particles. But nature saw to their stability. Another extremely fortunate property for us is the property of the neutron to achieve longevity when associated with protons. It is meaningless to speculate on whether this is chance or law; the important thing is that the fundamental building blocks of the world are stable.

The "chance", which made possible the creation of the material world, is based on strict prohibition laws according to which protons and electrons cannot decay. It is another matter where the prohibitions arise and why, in spite of them, the particles concerned nevertheless do have a half-life—however great, yet not infinite. But, paraphrasing the well-known proverb, we can say that man can ask so many questions that even nature is incapable of answering them.

We have, however, been rather carried away by philosophical problems of natural science. We have, of course, merely given the physicists elaborating "mad" ideas destined to encompass the visible and invisible world their due. But we have thereby violated the equilibrium between

theory and experiment, which should always be faithfully maintained.

For the experimenters, as one could have suspected, did not let the grass grow under their feet. More, they confronted the theoreticians with an accomplished fact that caused them to revise many of their theoretical conceptions.

It began some time ago, but it was only recently that the theoreticians began to realize all the implications of the revolutionary upheavals it caused.

INVASION OF RESONANCES

In 1952, Enrico Fermi, studying pion scattering by protons, discovered a new short-lived particle. In his experiments he bombarded protons with a beam of pions of different energy. Pions passing fairly far from the protons were hardly deflected from their initial paths, those colliding with protons were scattered. The scattering pattern was supposed to provide information about the sizes of the particles. Otherwise the experiment seemed to hold no great promise of surprises. But when the pions' energy reached 200 MeV their scattering suddenly increased sharply, followed by an equally sudden decrease when the energy was further increased. The pattern was that of a resonance peak corresponding to an energy of 200 MeV, which subsequently gave the name to a whole class of particles.

The new phenomenon had to be explained. The sharp increase in scattering observed by Fermi could have happened if the proton targets had suddenly ballooned a thousandfold in size; then, naturally, more pions would hit them and, accordingly, scatter. But it would be absurd to imagine such a sudden expansion for no obvious reason. It was suggested that in some pion-proton collisions short-lived particles, called resonances, are produced, which quickly disintegrate into pions. These secondary pions are responsible for the scattering peak discovered by Fermi.

Since 1960 about one hundred strongly interacting resonance particles were discovered. But before discussing this class of particles let us recall the experiments in which the first antinucleons were produced. As noted above, the first stage in the transmutation of a nucleon-antinucleon pair is its decay into pions. Strictly speaking, this is not at all necessary. Nucleon annihilation may produce, along

with pions, short-lived resonance particles: a neutral omega particle which decays into three pi mesons, and a rho particle which decays into two pi mesons and can exist in all charge states, positive, negative, and neutral.

Some time ago theoreticians had postulated that nucleons should contain omega and rho particles. These resonances were discovered only in 1961. Short-lived particles cannot be registered by instruments and the only indication of their existence is the energy and momentum distribution in long-lived products of nuclear interactions. The omega meson, for instance, was discovered by studying the momentum and energy of pions created in proton-antiproton annihilation. The rho meson was discovered in a similar analysis of the results of collisions of negative pions with protons.

In the study of resonances, it must be said, the experimenters left the theoreticians far behind and discovered a number of unpredicted particles. In particular, the eta zero meson, a neutral particle of mass approaching 1070 electron masses and decaying into the complete spectrum of pions, negative, positive, and neutral, was discovered in the reaction products of a deuteron-positive pion event.

In spite of their short lifetime (10^{-23} -10^{-22} sec), which in principle precludes their direct registration, physicists have learned to determine the mass, lifetime and other important characteristics (spin, parity, etc.) of resonances. They all take part in strong interactions, and none of the conservation laws prohibit their disintegration. Here is one example. Assume that five pions were produced in a proton-antiproton annihilation event:

$$p + \bar{p} \longrightarrow \pi^+ + \pi^+ + \pi^- + \pi^- + \pi^0$$

A physicist analysing particle tracks in a bubble chamber comes to the conclusion that some of the pions are the decay products of a single particle, suggesting that the reaction as written down above presents only the end result of a two-stage process. First an ω^0 meson is created in the annihilation event:

$$p + \bar{p} \longrightarrow \omega^0 + \pi^+ + \pi^-$$

in turn it decays into the full complement of pions:

$$\omega^0 \longrightarrow \pi^+ + \pi^- + \pi^0$$

Even though the ω^0 meson had travelled no measurable distance from the point where it was born, the end products uniquely testify to the fact of its existence.

When we say "resonance", "resonance particle", "resonance quasiparticle" we as it were are emphasizing that these ephemeral inhabitants of the microworld differ from "full-fledged" particles. This is not accidental. Fermi wasn't sure whether resonances could be strictly called particles or were simply associations of known inhabitants of the microworld. By now, however, the doubts have been dispelled. Practically all resonances are particles in the same right as those discussed above. And they are just as "unelementary". Resonances can be said to head the hierarchal pyramid of particles. At the base lie the long-lived, eternal particles, whose welfare is supported by the conservation laws, and also particles not governed by strong interactions and possessing no mass. But the triumph of resonances is short-lived.

As we have seen, rho and theta mesons can be quickly converted to pions.

The unity of veteran elementary particles and resonances is based on special inner connections. Every strongly interacting particle has its own resonances with greater values of mass. The resonances' quantum numbers are, as a rule, also higher than those of the respective long-lived particles. Which probably supports the views of those who treat resonances as excited states of elementary particles.

Resonances brought a lot of trouble into the ordered system. The "resonance deluge" of recent years has increased the number of "building blocks" of the universe several times over and made classification schemes well nigh impossible. Every year new works appear describing a good dozen new particles. Improvements in experimental techniques will evidently swell their numbers even more. Gell-Mann, for example, thinks that the possible number of elementary particles may run into the thousands. The periodic table of chemical elements, even taking into account all known isotopes, will evidently lose in a comparison with the table of "elementary" particles. The inverted commas seem more appropriate than even before.

It is not surprising, therefore, that we come back to the question of whether particles can truly be considered elementary or not. Only now we must set the resonances in order and then consider them jointly with other particles.

The resonances have been broadly divided into the meson and the baryon groups. The criterion for this division is the baryon charge or baryon number B. As in the case of mesons, the baryon number of meson resonances is zero; for baryon resonances it is $+1$.

The classification of resonances is based on isotopic spin and on hypercharge, which is the sum of the strangeness and baryon number. Four resonances, η, ω, φ and f^0, have the same hypercharge (0) and isotopic spin (0), and the name η meson is used to denote them all. To distinguish these particles, which have different mass, spin and parity, their mass in mega-electron volts, spin and parity are written next to their symbol. Thus, for the omega meson we write Ω (782, 1^-) and for the π meson π (750, 1^-). The one and minus sign following the mass value denote the spin and parity. The π (750, 1^-), of course, represents three resonances in the table, positive, negative, and neutral, which corresponds to the three possible orientations of isotopic spin.

Thus order is gradually created in the resonance chaos. Although resonances are so numerous it is gratifying to see that they can be reduced to a few families.

Meson resonances, whose hypercharge is zero, have no antiparticles. The η resonances are their own antiparticles, while with π resonances, as with pions, the negative particle is the antiparticle of the positive and the zero combines particle and antiparticle. The antiparticles of resonances whose hypercharge is 1 (with mesons it coincides with strangeness) possess the opposite hypercharge, -1. All meson resonances except the η (548, 0^-) decay in strong interactions, and parity is, of course, conserved.

Strange meson resonances (kappa) always decay with the production of K mesons. As for the anomalous η (548, 0^-), it seems to decay as a result of electromagnetic interaction. Its lifetime is two or three orders of magnitude longer than of other resonances. Strangeness is, of course, conserved, remaining at zero before and after decay.

Yet all is not well in the realm of resonances. There are several particles with mass around 1,200 MeV which do not fit into the scheme. Some of them decay into a meson and another meson resonance. These are as it were secondary resonances. Without listing all these mysterious quasiparticles, we shall cite the example of the A resonance with

mass 1,200 MeV which decays into a pion and a rho particle, and the *C* resonance whose mass is estimated at 1,175 to 1,230 MeV.

Besides resonances producing two or three mesons on decaying there are several prolific resonances that yield four pions. There is the Brobdingnagian *B* resonance with a mass of 1.22 GeV, often called a Buddha meson, which decays into a pion and an omega meson, i.e., ultimately into four pions. Its name is not due to its mysterious properties, although its spin and parity are not yet definitely known, but to the fact that it was discovered by a team including a physicist from South Vietnam. At the time the world was shaken by the news of another case of self-incineration by a Buddhist priest, hence the name.

The λ resonance, with a mass of $1{,}250 \pm 30$ MeV, also decays into four pions, two positive and two negative. But the creation of four mesons is not the record of the resonance world. In 1964, a five-pion resonance was discovered, and even this may not be the limit. The number of multiple-meson resonances is literally snowballing and threatening to swamp the physical journals. But, as was once the case following the discovery of X-rays, a number of spurious resonances began to appear among the newly discovered events. Thus, it had seemed that a new two-pion resonance was observed in a proton-deuteron collision. It was even called an *ABC* resonance from the first letters of the names of its discoverers. The discovery was not subsequently confirmed.

"Spurious resonances," writes Corresponding Member of the Soviet Academy of Sciences K. I. Shcholkin, "are not due to any mistakes in the experiment, and certainly not to evil design. They appear as a result of an extremely subtle effect which may occasionally yield a peak on a phase curve which is taken for a resonance. When the kinetic energy and, accordingly, the velocities of scattering particles are small the latter remain for a comparatively long time within the sphere of action of nuclear forces of neighbouring particles. As a result one of them may stay coupled with an outside particle longer than another, and a peak appears on the phase curve. It is sufficient to increase the energy of the colliding particles responsible for the three scattered ones: the relative scattering speed increases, they cease to 'adhere' and the peak on the curve disappears."

Thus, there is a reliable means of distinguishing between spurious and true resonances. As soon as the energy is raised the imposters fall apart like a house of cards.

Meson resonances often appear together with baryon resonances. Amongst the latter scientists commonly distinguish nucleon states (hypercharge +1) and hyperon states with hypercharges 0, —1 and —2.

Nucleon states had originally been denoted N^*, but as more and more of them began to appear the asterisks were replaced by superscripts. The same happened with hyperon states of zero hypercharge for which, as in the case of meson quasiparticles, the respective parameters are given in parentheses.

Nucleon resonance decay always produces a nucleon, as otherwise two conservation laws would have been violated: strangeness and baryon charge. Resonances of zero hypercharge, which corresponds to —1 strangeness, must decay with the creation of a particle of the same strangeness. It may be an anti-K meson or one of the hyperons, lambda or sigma. If an anti-K is produced the conservation of baryon charge requires the appearance of a nucleon as well. Hyperon production, however, is more common.

The family of hyperon states of hypercharge —1 is small, but there are grounds for expecting new members to supplement it. It goes without saying that the strangeness and hypercharge of the Ξ hyperon, which belongs to this family, is conserved in its decay into a pion and a xi hyperon.

Hyperon states of hypercharge —2 are restricted to one particle, discovered fairly recently. This is the famous omega-minus hyperon, of which we shall speak later on. At present note that the particle is stable and no resonances of such hypercharge have so far been discovered.

But return to nucleon resonances. An interesting feature of this family is the existence of three particles with an isotopic spin of 3/2. These are the so-called Δ resonances. The values of the isotopic spin projections (3/2, 1/2, —1/2, —3/2) are associated with electric charges of +2, +1, 0 and —1, i.e., each resonance can occur in four different charge states.

We have made a rather cursory acquaintance with the resonance families. It is high time to achieve some order in this burgeoning world and undertake a final classifica-

tion of its inhabitants. But before introducing this new classification, suggested by Murray Gell-Mann, we must go back almost two decades.

ALL WAYS LEAD TO THE "EIGHTFOLD WAY"

The idea that π mesons may not be elementary but comprise nucleons and antinucleons was first voiced by Fermi and Young in 1949. Other speculations followed, which gained in diversity as the number of particles increased. There was the Markov model, the Sakata model and a dozen others. They all assumed the existence of some fundamental particles out of which all the others are built, just as the nucleus is made up of nucleons. All this has been discussed above.

And yet, there is still no theory of strong interactions which would offer a mathematical description of the whys and wherefores of particle association and transmutation, and there is unlikely to be one for quite some time. This would seem to preclude the possibility of deriving any quantitative conclusions or predictions from any composite model which could be verified experimentally. This is, however, possible, since the models possess certain symmetry properties.

The known symmetries can be subdivided into two classes. Firstly, spatio-temporal symmetries. To them belong the properties of space homogeneity and isotropy, which is to say that every physical law is the same for every point of space and every direction through it. Similarly, the equations including time are symmetrical with respect to past and future. We have already spoken of time inversion. These symmetries are very important, as the principal conservation laws (energy, momentum and moment of momentum) are associated with them.

But besides spatio-temporal symmetries there are also internal symmetries independent of them. In the case of strong interactions this internal symmetry is linked with the fact that nuclear forces are independent of particle charge. For example, the proton and neutron have almost the same mass, but the neutron has no charge (hence the two are as it were asymmetrical). At atomic distances, where electromagnetic forces play the main part, this difference is extremely significant. But at very small distances

(within the nucleus, for example), when strong interactions become tens of times greater than electromagnetic, the proton and neutron can be regarded as two slightly differing states of one particle, the nucleon, as they are symmetrical with respect to strong interactions. These groups of similarly interacting particles are called isotopic multiplets. In essence this is a new formulation of a familiar problem.

As new particles were discovered it was found that isotopic multiplets can be arranged in larger families of supermultiplets possessing the same baryon charge, spin and parity. Here we bring together particles not only with different electrical charge, but with different strangeness as well.

The existence of superfamilies is an indication of a symmetry that is in a sense more general than isotopic invariance. From the very beginning this classification yielded an important discovery. When it was enunciated all the particles of the ten-member baryon family in the diagram on page 244 had been known, with the exception of the one at the apex of the triangle. Gell-Mann calculated that the place had to be filled by a particle of negative charge, strangeness —3, and 1,670 MeV mass. Several laboratories launched a search for it, and a year later the omega-minus hyperon was discovered.

How does one visualize the formation of supermultiplets on the premise that their members are made up of other, more fundamental particles?

Before answering this question an important reservation must be made. Attempts to classify elementary particles embrace only baryons and some mesons. These strongly interacting particles were, at the suggestion of L. B. Okun, called **adrons**, as distinct from the lighter leptons. Adron means "powerful", "massive" in Greek. A unified classification which would include all particles, adrons as well as leptons, appears to be facing insurmountable obstacles. Nevertheless, the fact that leptons fail to fit into a system of elementary particles should not be regarded as a major drawback, for after all there are more than a hundred known adrons but only nine leptons: the photon, two neutrinos, electron, positive μ meson and their respective antiparticles (with the exception of the photon).

We have already mentioned the attempt of Fermi and Young to develop a system of elementary particles based on protons and neutrons and their respective antiparticles.

At the time the only known members of the adron family were the nucleon doublet and π mesons. The π^+ meson could be regarded as a bound state, as a kind of proton-antineutron combination: the π^- meson could be "assembled" from an antiproton and a neutron; finally, the zero pion could be imagined as a proton-antiproton or neutron-antineutron combination.

The Fermi-Young scheme can be expanded. Thus, two nucleons with spin $^1/_2$ can be used to make up a triplet with zero spin and baryon charge, and electrical charges of $+1$, 0 and -1. If we take four or, say, six nucleons and antinucleons we can construct several other multiplets.

In fact, at one time it began to seem that the Fermi-Young scheme would yield a counterpart of Mendeleyev's Periodic Table for elementary particles. Then these hopes were dashed by the concept of strangeness, which has so often foiled hopes of clear and beautiful laws of the microworld. As we know, it was in the early fifties that strange particles began suddenly to pop up at every turn. Hyperons or K mesons cannot be composed of nucleon-antinucleon pairs possessing no strangeness.

This difficulty was overcome by the Japanese physicist Sakata. His scheme is based on three fundamental baryons (fundamental fields): the proton, neutron and lambda hyperon. Together with their antiparticles they are like the three pillars of the universe. Any meson or baryon can be represented as a combination of two or more of these particles. Mesons, in particular, are combinations of a fundamental particle and antiparticle. The bonds between them are so great that the mass defect closely approaches the sum of both baryons. According to Sakata's scheme, the positive pion is the product of proton-antineutron fusion, the negative pion is produced by neutron-antiproton fusion. The positive K meson comprises a proton and antilambda hyperon, the negative, an antiproton, and lambda hyperon. The structure of neutral mesons is more complex. Naturally the baryon charge of any such "composite" meson is zero and the other quantum numbers fully agree with the experimental values.

Here for example, is the structure of the positive sigma hyperon. It comprises a proton, which determines its electric charge, a lambda hyperon, responsible for its strangeness, and an antineutron to balance the baryon charges.

Sakata's fundamental fields constitute one isotopic doublet (p, n,) and one isotopic singlet (Λ). This is not accidental. More, by taking any three strongly interacting particles, two of which constitute an isotopic doublet and one a singlet, one can construct a new model in no way inferior to Sakata's.

Sakata's model did not survive for long, though long enough to achieve universal acclaim. This happened when physicists established a correspondence between the fundamental fields and three leptons: the neutrino, electron and negative muon. The exciting contours of a possible symmetry between the principal strongly and weakly interacting particles seemed to appear. This symmetry even received a name. As the idea was first expressed at the International Conference on High-Energy Physics held in Kiev in 1959, the hypothetical symmetry was named after that city.

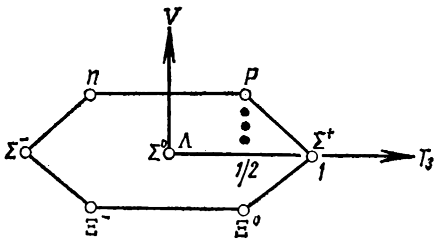
The Kiev symmetry held out the promise of a comprehensive classification of all particles, adrons and leptons. But then the discovery of a fourth lepton, the muon neutrino, mentioned above, shattered these hopes. This was followed by the deluge of resonances. Experiments began increasingly to contradict theory.

In 1961, Gell-Mann and the Israeli physicist Ne'eman independently worked out a new classification system. The mesons and baryons in it follow Sakata's general scheme, but instead of three fundamental baryons it has eight basic particles: p, n, Λ, Σ^+, Σ^0, Σ^-, Ξ^-, Ξ^0. Like Sakata's, Gell-Mann's and Ne'eman's mesons constitute a baryon-antibaryon pair. More baryons (and corresponding antibaryons) means much more possible combinations. The number of possible meson states, for example, exceeds the number of mesons so far experimentally observed.

Baryons in the new scheme come in pairs, which always include one of the fundamental baryons and a meson. The scheme provides for many possible baryons forming supermultiplets, or unitary multiplets, as they are also called.

Supermultiplets include several common isotopic multiplets differing in strangeness and/or isotopic spin. Generally speaking, unitary symmetry assembles particles with more or less similar properties in groups of eight or ten. It is assumed that particles of different strangeness or isotopic spins within the same unitary multiplet are nevertheless similar. Taking the multiplet mentioned above, the eight-

member baryon family p, n, Λ, Σ^+, Σ^0, Σ^-, Ξ^-, Ξ^0, we observe that all its members have half-integral spin, positive parity and more or less similar mass. They can be arranged at the apexes and centre of a regular hexagon produced on a graph of the dependency of hypercharge Y on $T_3=Q-Y/2$:



Unitary symmetry requires that all eight particles be absolutely indistinguishable. Actually, as we know only too well, they in fact differ substantially. One need but take a look at the table to remove any doubts on this score. The important thing is, however, that differences between the particles are revealed only in interactions, which give each its specific traits. This moderately strong interaction removes the hypercharge and isotopic spin degeneracy. Thus a supermultiplet as it were breaks up into several ordinary isotopic multiplets.

What then is the difference between one supermultiplet and another? Hypercharge and isotopic spin have levelled out and only a moderately strong interaction recalls them to life. What remains? Spin? Parity? Mass? It is hard to determine mass precisely as its values in a split multiplet tend to differ. All one can speak of is its order of magnitude in each supermultiplet, of some averaged value obtained by somewhat mysterious means. With baryon charge we can achieve no more than its division into meson ($B=0$) and baryon ($B=+1$) unitary multiplets.

Still, characteristics such as mass, spin and parity, which reflect the most fundamental properties of particles, can be used as criteria for describing unitary multiplets. At least they do not vanish like smoke when a supermultiplet degenerates. The most important of the three is mass. It seemed that the average masses of different multiplets should differ more than the masses within the same multiplet. This, however, did not prove the case. Only with rare exceptions

could mass be used as a basic quantum number distinguishing one supermultiplet from another.

Meanwhile physicists stubbornly demanded answers to their questions from the new system. It was necessary to establish the number and type of isotopic multiplets that could exist within each unitary supermultiplet and how many supermultiplets there are in general.

The problem was resolved with the help of one of the most abstract departments of higher algebra known as group theory, which treats of various mathematical transformations.

Up till now we have refrained from speaking of the mathematical problems of physics. But today one of the most interesting pages in the physics of elementary particles is associated with group theory, so we shall have to deal with it in greater detail.

In 1910 the mathematician Oswald Veblen and the physicist James Jeans, author of a once popular theory of the origin of the earth, were discussing the reform of the mathematical curriculum at Princeton University. "We may as well cut out group theory," said Jeans. "That is a subject which will never be of any use in physics." Fifty years later Freeman Dyson, father of the so-called "Dyson sphere", wrote: "By an irony of fate group theory later grew into one of the central themes of physics, and it now dominates the thinking of all of us who are struggling to understand the fundamental particles of nature."

Evidently the future of science is predictable to a very low degree of probability. It is all the more difficult to define once and for all the place of mathematics in natural science. The connections between them are profound and diversified, perhaps as inexhaustible as science itself.

The two main concepts in group theory are "group" and "representation". A group is a set of operations possessing the property that any two of them performed in succession are together equal to another operation belonging to the set. For example, the three-dimensional rotation group O_3 is defined as the set of all rotations of an ordinary three-dimensional space about a fixed centre. Obviously, if R_1 and R_2 are any two such rotations the combination of them can be duplicated by a third rotation R_3. A representation of a group is a set of numbers and a rule of transformation of these numbers such that each operation of the group produces a well-defined transformation of the numbers. All this

may seem rather involved, but it is probably as clear as it can be made. It is not easy to present a popular exposition of abstract mathematical concepts. So perhaps some elementary algebraic symbolism will be helpful.

The transformations in a representation are restricted to being linear, that is to say, if a particular transformation sends p to p' and q to q', then it also sends $p+q$ to $p'+q'$. An example of a representation of O_3 is the set of three Cartesian coordinates (x, y, z) that determine the position in space of any point P. When a rotation R is applied, the point P moves to a new position P' with coordinates x', y', z', and this determines the rule of transformation for x, y, z. This particular representation of O_3 is called the triplet representation.

Now let us take a concrete case in the physics of elementary particles. As we know, there is a triplet of pions, and we can therefore imagine them as a triplet representation of a group O'_3, having the same abstract structure as O_3 but having nothing to do with ordinary space rotations. We can predict many of the properties of pions from abstract group theory alone without knowing anything about the intrinsic nature of the operations constituting O'_3. It turns out that all of these predicted properties of pions are confirmed by experimental data.

So much for group theory. Incidentally, the group O'_3 is known in physics as the "isotopic-spin group".

Finally we come to the unitary symmetry. The classification depends on a group U_3, which is larger and less familiar than O_3. To make U_3 understandable let us introduce a mechanical model that bears the same relation to the abstract group U_3 as the rotations in three-dimensional space bear to the abstract group O_3. This mechanical model is not supposed to exist in real world and is intended only as an illustration.

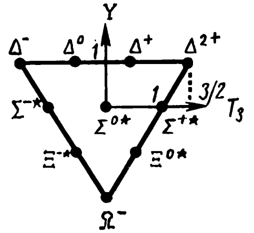
Consider a solar system in which the force of gravity varies directly with the first power of distance instead of with the inverse-square law. Suppose the planets to be small, so that their mutual perturbations are negligible. Each planet then moves independently in an elliptical orbit with the sun at the centre. These orbits all have the same period, the outer planets moving faster than the inner ones. We call the period of each orbit a "year", so that the positions of all planets repeat themselves at yearly intervals.

The motion of a planet can be specified precisely by two points in space denoted (P, Q), P being the position of the

planet now and Q being the position it will occupy in, say, half a year. Another planet travelling six months ahead of the first will be specified by $(Q, -P)$, where $-P$ means the point diametrically opposite P. The total energy of either of these planets is given by (OP^2+OQ^2), which is the sum of the squares of the distances of the points P and Q from the sun at O. The group U_3, as exhibited by this particular model, is defined as the set of all transformations of the planetary motions, subject to the following three restrictions: (1) the transformations are linear; (2) the transformations leave the total energy of each motion unchanged; (3) if two or more planets are moving in a given orbit, a transformation that takes one to a new orbit takes all.

For application to physics it is convenient to reduce U_3 to a smaller group SU_3. This is achieved by simply neglecting time. For SU_3 all motions belonging to the same orbit are regarded as identical irrespective of the time. Whereas U_3 transforms a planetary motion into another planetary motion at a particular time, SU_3 transforms an orbit into an orbit without reference to time. This theory is known as the eightfold way because the familiar superfamily of eight related particles was the first grouping suggested by it. And two more "eights" are suggested by the name. The first is the eight quantum numbers: the three components of isotopic spin, hypercharge and four unnamed numbers associated with "moderately strong" interactions. The other "eight" is reputed to refer to Buddha's statement that there are eight righteous ways to bliss. In addition to the eight-member structure, the eightfold way has led to superfamilies of 10, 27, and more members.

The SU_3 theory was invoked by Gell-Mann to predict the existence of a 10-member set of particles with the same spin and parity, depicted graphically as an overturned isosceles triangle:



Nine points in the diagram were filled by known particles. The point at the apex denoted Ω^- remained empty. The SU_3 theory predicted that the particle should have a baryon charge of 1, an electric charge of —1, a hypercharge of —2 and a spin of 3/2, the same as the other members of the set. The mass and parity (positive) of the singlet were also predicted by the theory. The famous omega-minus was discovered in February 1964 on bubble-chamber photographs made at Brookhaven. Three hundred thousand pictures were scanned to detect the first omega-minus.

It was a great triumph for theory, a remarkable proof that the abstract SU_3 symmetry actually exists in nature and governs the behaviour of strongly interacting particles.

Let us now jump over several more steps of the ladder leading from chaos to order and symmetry. The contours of this order are already apparent in the diversity of particles. The magic numbers 35 and 56 characterize the magic of elementary particles, the whole diversity of which have been classified into two major groups: 35 meson states and 56 baryon states. These states are easily listed and fitted into a scheme through which the contours of a new periodic system are beginning to emerge.

As of this writing, there are eight known mesons with zero spin: π^+, π^-, π^0, K^+, K^-, K^0, $\overline{K^0}$, η^0.

Nine mesons have unity spin: ζ^+, ζ^-, ζ^0, φ^0, ω^0, K^{*+}, K^{*-}, K_1^{*0}, K_2^{*0}.

This gives us a family of eight mesons with zero spin and a family of nine mesons, each with three states (spin 1). Hence we have $8\times1+9\times3=35$ mesons.

These 35 particles can be fitter in a table of $6\times6=36$ squares. True, one particle is missing, but this is as it should be: a corollary of group theory requires that an arrangement of 36 squares should contain 35 particles.

Now take baryons. Here we have 56 particles and, as we know, 56 antiparticles. This must be made clear at once as in the case of the mesons we lumped the particles and antiparticles together in one family.

To begin with, we write down (again!) the family of 8 baryons with half-integral spin: n, p, Σ^+, Σ^-, Σ^0, Λ, Ξ^0, Ξ^-.

Now the family of ten with spin 3/2: Δ^{2+}, Δ^+, Δ^-, Σ^{*+}, Σ^{*0}, Σ^{*-}, Ξ^+, Ξ^{*-}, Ξ^{*0}, Ω^-.

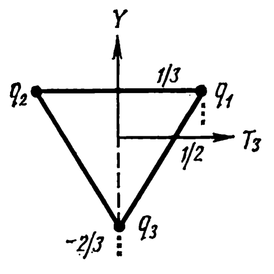
We thus have eight doublets and 10 particles with four spin states: $8 \times 2 + 10 \times 4 = 56$.

But, as mentioned above, there are quite a few known resonances which refuse to fit into any classification. The scheme is doubtlessly an ingenious one, but the "lone" F resonance, four-pion B resonance and some other mystery particles mar its beauty. Still, a substantial number fit into the two giant multiplets.

"The new classification," writes Academician Ya. B. Zeldovich, "covers only strongly interacting particles. Accordingly, it fails to include electrons, muons, neutrinos, and quanta. This is a wise self-restriction which may be the earnest of success."

Since the discovery of the omega-minus the number of works bearing on group theory snowballed so greatly that it would be hard even to merely list the publications on the subject. But the day finally dawned when the flow of information yielded something which caused even the "maddest" theoreticians to prick up their ears.

SU_3 symmetry (incidentally, not long ago a new classification of adrons was published based on SU_6 symmetry, and even on SU_{12} symmetry, but we shall not discuss them) yields one extremely interesting graph:



If we identify the points at the apexes of the triangle with real particles, as was done in the case of the eight-member and ten-member families, we obtain that there must exist particles with some astounding, to say the least, properties, namely fractional electric charges, 2/3 for q_1, $-1/3$ for q_2 and q_3, and fractional hypercharge!

The existence of these freak particles, as Professor Smorodinsky aptly described them, was postulated simultaneously by Gell-Mann and the Swiss physicist Zweig.

ENTER THE QUARK

The name "quark" was introduced by Gell-Mann, and he got it from James Joyce's *Finnegan's Wake*:

"—Three quarks for Muster Mark!
"Sure he hasn't got much of a bark
"And sure any he has it's all beside the mark.
"But O, Wreneagle Almighty, wouldn't un be a sky of a lark
"To see that old buzzard whooping about for uns shirt in the dark
"And he hunting round for uns speckled trousers around by Palmerstown Park?
"Hohohoho, moulty Mark!
"You're the rummest old rooster ever flopped out of a Noah's ark
"And you think you're cock of the wark.
"Fowls, up! Tristy's the spry young spark
"That'll tread her and wed her and bed her and red her
"Without ever winking the tail of a feather
"And that's how that chap's going to make his money and mark!"

What is known of these quarks the birds of the sea were "shrillgleescreaming" about?

Firstly, they have fractional electric charges.

Their baryon charges are all $+1/3$ ($-1/3$ for antiquarks).

The third quantity is spin. Like so many other particles, they have spin $+1/2$.

To act as building blocks for other elementary particles quarks must also possess strangeness. Gell-Mann postulated that two have zero strangeness and one, -1.

Finally, all elementary particles possess one more important characteristic, mass. As long as a particle is moving all alone in vacuum without interacting with anything its mass remains constant. But as soon as it becomes part of a nucleus a portion of the mass turns into kinetic energy of motion or radiation. For example, when four protons, whose total mass is 6.690×10^{-24} g, join to form an alpha particle (a helium atom nucleus), the mass of which is 6.644×10^{-24} g, 0.046×10^{-24} g, or approximately 0.7 per cent of the initial four protons' mass, turns into energy.

This is the thermonuclear reaction that generates the energy of the sun and stars in the universe and of the hydrogen bomb on earth.

The reverse process is also possible. If a particle flying at tremendous speed collides with another one new particles can be created whose total mass is greater than the combined mass of the colliding particles by the amount of absorbed kinetic energy.

These complex interactions of particles accompanied by energy emission and absorption are observed in all kinds of accelerators from Dubna, in the Soviet Union, to Brookhaven in the United States. And if not for one more fantastic feature of quarks their transmutations would not have escaped the eyes of physicists. So far, however, not a single quark has been found either in streams of cosmic particles or in manmade beams produced by accelerators.

That quarks have never been observed in common physico-chemical research can be explained by the fact that they occur very rarely in a free state and therefore the possibility of their being detected is very small. That they have not been produced in collisions generated in modern accelerators may mean no more than that their mass is so much greater than that of protons that the kinetic energy imparted to bombarding particles by accelerators is not sufficient to create them.

The mass of the quark with non-zero strangeness is one and one-half per cent greater than that of either of the other two, the mass of which is tentatively postulated to be 10 times the mass of the proton.

It turns out, then, that three quarks whose combined mass is 30 proton masses go into the making of one proton, which means that 29 proton masses, or 97 per cent of the initial mass, turn into energy.

Compare this with the 0.7 per cent "vanishing" mass in thermonuclear reactions—a difference of 140 times.

Denoting the quarks p, n and λ their properties can be tabulated as follows:

Quark	Electric charge	Baryon number	Strangeness	Spin
p	+2/3	+1/3	0	1/2
n	—1/3	+1/3	0	1/2
λ	—1/3	+1/3	—1	1/2

How can these three quarks (or antiquarks) be used to produce the diversity of particles in the burgeoning family of adrons?

As a quark's baryon charge is 1/3, it takes three quarks

(or four quarks and one antiquark, etc., in more complex cases) to make one baryon. If their spins are all orientated in the same direction the resultant spin of the baryon will be 3/2. Out of three different kinds of particles a total of 10 different symmetry combinations can be constructed. This is tabulated as follows, with the electric charge and strangeness from the quark table in brackets under each combination:

	$\lambda\lambda\lambda$ (—1, —3)		
$p\lambda\lambda$ (0, —2)		$n\lambda\lambda$ (—1, —2)	
$pp\lambda$ (+1, —1)	$pn\lambda$ (0, —1)		$nn\lambda$ (—1, —1)
ppp (+2, 0)	ppn (+1, 0)	pnn (0, 0)	nnn (—1, 0)

According to electric charges and strangeness this group of particles belongs to the ten-member baryon family presented above as a triangle.

Thus, we have obtained a ten-member baryon family with all the quantum numbers that characterize it. The average masses of particles of this superfamily reading upward line by line are 1,236, 1,382, 1,529, and 1,675. The differences between neighbouring numbers are, respectively, 146, 147 and 146. This leads to the suggestion that the p and n quarks have approximately the same mass and the λ quark is 146 MeV heavier.

Now take the eight-member baryon family, which can also be constructed from quarks using the same rules:

$p\lambda\lambda$ (0, —2)		$n\lambda\lambda$ (—1, —2)
	$pn\lambda$ (0, —1)	
$pp\lambda$ (+1, —1)	$pn\lambda$ (0, —1)	$nn\lambda$ (+1, —1)
ppn (+1, 0)		pnn (0, 0)

The quark combinations are the same as in the ten-member family, but the particles must have spins 1/2 and they should not duplicate those appearing in the ten-member family. According to the rules of quantum mechanics, a

particle's spin can assume only such directions that its projection on an axis z takes certain values differing from one another by unity. Thus the spin projection of each separate quark can be only $+1/2$ or $-1/2$.

These propositions were sufficient to explain the absence of the apex members (*ppp*, *nnn* and $\lambda\lambda\lambda$) of the ten-member family and the duplication of the middle member $pn\lambda$. We shall, however, not go into the reasoning.

The important thing is that all the baryons in our system have been constructed. Before going over to mesons let us see how the mass rule is observed for the eight-member baryon family. The average masses reading upward line by line are 939, 1,173 and 1,318. The respective differences are 234 and 145. Thus for some unexplained reason only the second difference is according to prediction.

The baryon charge of mesons is zero and, consequently, in the simplest case each meson should be composed of a quark and antiquark. Out of three quarks and three antiquarks nine such combinations can be achieved:

$\bar{p}\lambda$ (—1, —1) $n\bar{\lambda}$ (0, —1)

$p\bar{p}$ (0, 0) $n\bar{n}$ (0, 0) $\lambda\bar{\lambda}$ (0, 0)

$\bar{p}n$ (+1, 0) $p\bar{n}$ (—1, 0)

$n\bar{\lambda}$ (+1, +1) $\bar{n}\lambda$ (0, +1)

If the spins of the quarks are oppositely orientated we obtain an eight-member faimly of π mesons with zero spin; if the spin orientation coincides we have a family of ρ mesons with spin 1.

In the middle of this scheme there are combinations of quarks with their respective antiquarks. Such a pair can annihilate, just as a colliding electron-positron pair annihilates with the emission of electromagnetic field quanta — photons. On the other hand, it is possible for an electron-positron pair to be produced through photon absorption. It is natural to assume that quark-antiquark pairs can undergo similar annihilation and re-creation processes, such that each pair, $p\bar{p}$, $n\bar{n}$ and $\lambda\bar{\lambda}$ can turn into any other.

Now the scheme is complete. The particles not included in it (with spins 2 or 5/2, etc.) can also be constructed out of

the p, n and λ quarks and their antiquarks in combinations of fours or fives. The quark theory thus yields all the known elementary particles and predicts undiscovered ones needed to fill the tables. For a hypothesis this is already enough: it must be logically sound, explain points unexplained by other theories, not contradict known facts, and predict new ones. The quark model does just that.

Scientists have invented other fundamental particles besides quarks to explain the diversity of the microworld. They were most concerned with the "unnatural" fractional electric charges of quarks. A result was a hybrid theory of "normal" quarks and a negatively charged protobaryon that accounts for the baryon charge. According to this theory the electric charge of quarks is $+1$, 0 and 0, and the baryon charge is 0.

A sufficiently satisfying classification of elementary particles was developed which employs nine baryonets with a baryon charge of 1/9 and integral electric charges. But here the motivations seem to have been simply habit and prejudice as a fractional baryon charge is, of course, no better than a fractional electric charge and baryonets are as chimerical as Gell-Mann's quarks.

All these chimeras were invoked to overcome the difficulties bred by the rapid increase in the number of elementary particles. But there was one experimental fact which neither the old physical theories, nor protobaryon and baryonet hypotheses could resolve. Except the quark hypothesis, which boldly tackled it. We are speaking of magnetic moment.

The simplest thing would have been to assume that magnetic moment appears because charged particles turn on their axes with constant velocity. But then the chargeless neutron should have no magnetic moment no matter how fast it turns. Experiment, however, shows that the neutron's magnetic moment is 0.685 that of the proton and that it is directed not along the spin axis, as in the proton, but oppositely, as in the electron. No amount of ingenious juggling with charge configurations within the neutron could explain its magnetic properties.

But the quark hypothesis did.

However, in spite of the optimists, quarks remain no more than a hypothesis, and an extremely questionable one at that, until they are discovered experimentally. Attempts have already been made and it must be said that the initial results are not at all hopeless.

PART FOUR

Space. Time. Vacuum

VON LAUE: "NOTHING INTRIGUES MAN MORE THAN THE PROPERTIES OF SPACE AND TIME"

Classical physics treated of space and time as possessing preordained properties derivable from the simplest axioms. Also, space was considered to be the study domain of mathematics, not physics. For more than two hundred years physicists spoke of "absolute" true mathematical space. Newton defined time as follows: "Absolute, true, and mathematical time, of itself, and from its own nature, flows equably without relation to anything external, and by another name is called duration."

This definition was not far in advance of one given by St. Augustin, who claimed that he had a clear idea of what time was until he was asked to explain what it was, and ceased to understand it at all as soon as he began to explain it.

The revolution worked by the genius of Einstein made space and time full-fledged subjects of physical research and stripped them of the authority of "*a priori* forms".

In an epitaph for Sir Isaac Newton Pope wrote:

Nature and Nature's law lay hid in night:
God said, let Newton be! and all was light.

To which Sir John Collings Squire responded:

It did not last: the Devil howling 'Ho!
Let Einstein be!' restored the status quo.

This answer was an expression of a widely held idea.

For it seemed to many that rejection of classical mechanics was tantamount to a rejection of scientific knowledge of the material world.

Actually, of course, the world picture drawn by modern physics is distinguished by a lucid inner logic and even simplicity.

Einstein's basic idea was that the properties of space and time should not be regarded as given *a priori* but deduced from experience. Nor need these properties be always and everywhere the same: they change from point to point and from instant to instant. But of this a little later. Meanwhile we are about to embark on a journey full of paradoxes, unexpected metaphors and, alas, not always readily understandable analogies.

Since time immemorial man has sought to fathom the motions of heavenly bodies. The vast material accumulated by generations of astronomers enabled Kepler to formulate his famous laws of planetary motion around the sun. Newtonian mechanics to some degree absorbed and explained these laws, since the laws of planetary motion were deduced from more general laws. Here was achieved the first decisive success of physical theory.

To appreciate the better the novelty of Einstein's theory we shall have to recall the fundamentals of Newtonian mechanics.

All mechanical motions of bodies are relative. They can be determined only in relation to other bodies. As said above, a body's position in space is given by a coordinate system. The coordinate axes connected with the body with respect to which the motion is described form a frame of reference.

Frames of reference in which all accelerations are caused only by interactions between bodies are called inertial frames. A body that does not interact with anything else moves uniformly in a straight line with respect to an inertial frame.

All these are known things. Now let us introduce some doubts. Do true inertial frames exist? Evidently not, though there are very many that come very close to the definition of one. Every system has its degree of inertia. Take a train standing at a railway platform. One frame of reference is connected with the platform, the other with the train. The conductor blows his whistle and the train starts. The passengers feel a slight jolt and sway in the direction opposite the train's motion. This jolt (acceleration) has not been caused by any interaction between train and passengers. It is a consequence of the nature of the train's motion. No one on the platform felt the jolt. Hence the frame of reference connected with the platform is more inertial than that connected with the train.

Now if we wish to detect any deviations from inertiality in the frame connected with the platform, that is, the earth, this is easily done. Thus, a stone dropped from a great height will be deflected slightly to the east of the plumb line by the earth's rotation. The plumb line in this case indicates the direction of the interaction between the stone and the earth. In Newtonian mechanics this interaction is known as the force of gravity. The stone deviates from the direction of the force of gravity owing to the earth's rotation on its axis, that is, owing to a certain noninertiality of its motion. Any interaction between bodies is expressed in the terms and dimensions of force, which need not necessarily be gravity.

Therefore, going over to Newton's second law, we can say that the measure of any force is the acceleration it imparts to a body.

If a force imparts the same acceleration to different bodies, these bodies are said to have the same mass. A body's mass is independent of the forces that happen to be acting on it at a given moment. This is by no means a self-evident truth. It derives from experimental data and, as we already know from our first talk on relativity theory, the constancy of a moving body's mass is only an approximate law valid for comparatively small speeds. At relativistic velocities this law does not hold.

But acceleration in inertial systems may be caused not only by interactions of bodies. If an acceleration due to a system's inertiality (the jolt felt by passengers in a train) is multiplied by the accelerated body's mass we obtain the magnitude of the inertial force.

We can observe the difference between inertial force and interaction forces inside a railway coach (or a submarine). We shall repeatedly make use of this imaginary railway coach which will serve as a fine physical laboratory. Since Galileo's ship with its closed cabin, this laboratory has been migrating from one book to another.

Inside our laboratory we have two cast-iron spheres, one big and one small, attached to the walls by two identical springs. If we extend the springs to an equal length and then let them go the accelerations of the spheres will be in inverse proportion to their masses. But these same two spheres, when not attached to the walls, will receive exactly the same acceleration when the train starts or stops suddenly.

Therein lies the main difference between inertial forces and interaction forces.

There is, however, one interaction force which imparts all bodies, irrespective of their masses, the same acceleration. This force is gravitation, the force with which the earth attracts bodies.

The remarkable and inexplicable property of gravity was first established experimentally by Galileo, who studied free fall by dropping bodies from the top of the famous leaning tower of Pisa. No other interaction force—elastic, electric, magnetic, the drag of media on moving bodies—possesses this property.

The equivalence gravitational and inertial forces—the independence of the accelerations they impart on the masses of the bodies concerned—this is the key to the universal generalization of classical mechanics known as Einstein's general theory of relativity. This is a consequence of our departure from the textbook definitions of Newton's laws we learned at school.

In our laboratory coach we can create conditions in which it is impossible to distinguish between inertial force and gravitational force. If the coach, with all the windows shuttered, is made to move horizontally along the railway track with a uniform acceleration, a plumb line suspended from the ceiling will deviate from the direction people on the platform would call vertical. The plumb line, and, of course, all objects in the coach, behave exactly as if the coach were travelling at a uniform velocity up a hill, and the force of gravity were given by the sum of the actual gravity force and the inertial force in the coach moving horizontally with a horizontal acceleration. In both cases all bodies receive the same acceleration. Therefore, using only a balance and not knowing the true strength of the gravitational force, we have no way of determining whether the coach is actually moving uniformly up a gradient or with acceleration horizontally.

The laws of nature do not change if the motion of bodies is referred to inertial frames of reference. This is the essence of Galileo's relativity principle. Einstein's special theory of relativity extended the principle to electromagnetic phenomena. The apparent similarity between inertial forces and gravity within a small spatial domain, such as our coach, enabled Einstein to carry out one more generaliza-

tion. For if one treats gravity and inertial forces as equivalent, then the laws of motion are the same in inertial and noninertial frames of reference. This is the starting point of the general theory of relativity, for which the equivalence of forces in any spatial domain, however small, is sufficient.

A complete identity between gravity and inertial forces cannot be achieved. The example of a rotating body demonstrates that the centrifugal inertial forces increase with the distance from the axis of rotation. For the force of gravity in space not filled with matter this dependence on a coordinate system is unattainable.

In the general theory of relativity Newton's gravity law is no more than a first approximation, a truth of the lowest order. But relativity does not offer any more exact expression of force. It introduces a new quality. Einstein's theory of gravitation offers a new interpretation of the very essence of interaction, which is why this interaction cannot be expressed in simple Newtonian formulas.

At the present level of knowledge the concept of force acting between bodies is becoming increasingly unsatisfactory. If we believe, with Newton, that force is inversely proportional to the square of the distance, however great that distance is, then one must accept as axiomatic that a body acting on another as it were knows in advance where the other body is located. And not only "knows" but also instantaneously "chooses" the exact force needed to act on it. In other words, such interaction takes the form of action at a distance. If nature really did operate on the action-at-a-distance principle we would have had an excellent means of instantaneously transmitting signals over any distance. All we would have to do is to move a body for all bodies in the universe to instantaneously experience some change in the gravity force. Such a signal would make it possible to set the same time on all the clocks in the universe regardless of their relative motions.

But even on the scale of the earth clocks are synchronized, as we know, by radio, i.e., with the help of electromagnetic signals. They travel very fast indeed, but nonetheless the speed of light is finite. If all the clocks being compared are at rest relative each other, the correction for the time lag in the arrival of the signal to more distant clocks is easily made. But if one clock is moving relative the others, taking into account the time lag will lead us along the road which

Einstein's reasoning had followed. As we know, in 1887 Michelson showed that in vacuum the velocity of light is the same with respect to all bodies; in 1905, Einstein showed, in his special theory of relativity, that absolute motion cannot be determined for electromagnetic phenomena, just as for moving bodies.

If one body were emitting electromagnetic waves propagating with the same speed in all directions while another were emitting them in some preferential direction at a greater speed we could consider the first body to be absolutely at rest and the second absolutely in motion. But there is no such thing as either absolute rest or absolute motion. A simple set of calculations reveals that when the clocks of two bodies moving with respect to one another are checked the one on the body regarded at rest will always be showing more time. But both bodies can be regarded as resting with equal right! This is just where the startling newness of the theory and its remarkable conclusions lie. The lag of the clocks is reciprocal, and it is the greater the closer the relative velocity of the body approaches the speed of light.

This is true not only of the mechanical time keepers we call clocks or watches. Every recurrent physical, chemical or biological process obeys the law.

We cannot say whether there is any way of determining time without resorting to manmade or natural clocks. At the same time it is impossible to imagine how one would go about measuring time without some sort of clock, whether it be a simple weight-driven affair, an atomic clock, a water clock, heartbeats or the burning of a candle. On the other hand, we know of the constancy of the speed of light in vacuum. The conclusion thus follows that it is impossible to establish some universal absolute time: every moving body has its own proper time. This important conclusion drawn by Einstein enabled him to extend Galileo's relativity principle to electromagnetic processes.

Now we can return to Newton's law. As it is quite impossible to determine absolute time by attempting to synchronize clocks with the help of electromagnetic signals, the possibility of doing so with the aid of an instantaneously transmittable gravity force seems highly questionable.

It is obvious, therefore, that the law of gravitation should at the very least be formulated in such a way as to remove the contradiction with the conclusions of special re-

lativity. After all, one can hardly assume the existence of two times: absolute, deriving from gravitation, and relative, determined by eletromagnetic signals. As said before, the key to the rectification of Newton's law lies in the equivalence of inertial and gravitational forces.

We can describe an electromagnetic field at every point of space and at every moment of time in terms of the motions of trial electric charges, just as a gravitational field is described by the motion of a trial mass. Newtonian mechanics requires that, in the absence of gravitational field and all other forces, a trial mass move uniformly in a straight line with respect to an inertial frame of reference. In a gravitational field a trial body receives an acceleration that is independent of its mass. In small spatial domains, however, acceleration due to gravity in an inertial frame is physically indistinguishable from acceleration due to the noninertiality of a frame of reference. In a noninertial frame a trial mass is assumed to be moving freely.

The history of science has repeatedly demonstrated that the formulation of a law of nature is the more exact the less it depends on the attitude of the observer. The laws of nature are objective. This premise enabled Einstein to develop such a theory of gravity that the law of motion in a gravitational field is physically equivalent to the law of free motion. To explain the greater curvature of the path of a trial body close to local masses, Einstein assumed that the properties of space and time change from point to point and from instant to instant.

The general theory of relativity treats space and time as physical entities whose properties are inseparable from the matter moving in them. There is no motion outside of space and time, and there is no space or time without motion. One newspaperman once asked Einstein to express relativity theory in a single sentence. The great physicist replied: "Formerly people thought that if matter disappeared from the universe space and time would remain, relativity theory declares that space and time would disappear together with matter."

A FLAT WORLD AND THE FOURTH DIMENSION

Thus, for the first time in the history of physics, space and time can be said to have landed on the laboratory

table. The geometry of the world became a part of physics. It was no longer possible to proceed from speculative geometric postulates. Experiment knocked boldly on the door of the castle of geometry. The postulates of Euclidean geometry, familiar to us from school days, acquired a new quality. They too appeared before us as generalized experimental facts, only relating to small spatio-temporal domains. In large domains, on the scale of the Galaxy, they are no longer applicable. More precise and more general geometrical laws are required which would be inseparably linked with the laws of gravitational field, be an integral part of them. If there are no other field besides gravitational, the free motion of bodies becomes dependent solely on the geometry of the world. Einstein's law of gravity represents the dependence between the geometry of the world and the motions of large masses: stars and galaxies.

Let us examine how the properties of space and time determine the motions of bodies, of those same trial bodies which possess the interesting and exceedingly important property of being subject to the action of gravitational field without, owing to their negligible dimensions, being capable of affecting it in any way.

It is common in presenting a popular exposition, of general relativity theory to introduce an analogy with an intelligent two-dimensional being. Flatland, as the two-dimensional world can be called, is an utterly fantastic place, all the more so because our flatland traveller must be quite incapable of sensibly visualizing the direction of what we would call "up". It is with the utmost regret that I confess my inability to think of any better analogy and therefore invite you to imagine our flat traveller walking in his flat paper-sheet world. This world, whose surface the traveller cannot leave, is a model of our three-dimensional Euclidean space.

If we endow the flat world with a degree of elasticity we can bend or stretch it. Experience tells us that a two-dimensional surface is curved in three dimensional space, but we can imagine a curved surface beyond which nothing exists. Now, if we place a heavy sphere on a flat elastic surface the latter will bend about the sphere. The two-dimensional man will not notice this. But if we drop a small bead on the surface it will roll down the depression toward the sphere. To the flatlander it will seem that the two bodies are at-

tracted to each other. This is not a model of Einstein's gravitational theory but a very general analogy. In curved space the shortest distance between two points is not a straight line but a curve, a geodesic curve. In flat space the inertia law makes free motion be rectilinear. In curved space that same law describes free motion along a geodesic curve. If our flatlander lived on the surface of a sphere the shortest distance between two points for him would be an arc segment. It is along such arcs that a freely moving particle travels on a sphere. But to the flatlander these will be "straight" lines. However, he doesn't have to leave his world to discover that it is curved. All he has to do is circumnavigate it or, simpler still, add up the angles of a triangle and ascertain that the sum exceeds 180° to draw the conclusion that the properties of his world in large domains differ substantially from those in small ones.

The properties of shortest distances change together with the surface on which they lie. Thus, on the surface of an egg the sum of the angles of an isosceles triangle is greatest at the sharper end. A traveller on an egg-shaped world would be able to establish that his "space" is not homogeneous.

In much the same way we can determine whether our four-dimensional space-time is flat or curved. All we must do is investigate its intrinsic geometry and compare it with the postulates of Euclid or the more general postulates of Lobachevski-Riemann.

If we accept that in the four-dimensional world bodies move along the shortest distances through space, then the rotation of the planets around the sun must evidently obey this rule. But is the sun's gravity large enough to curve space so substantially? Or take the moon circling the earth: can it be moving in such a warped space?

These questions, it must be said, are miss-stated. They arise from a failure to grasp the essence of the problem. They derive logically from our concepts of three-dimensional space, whereas general relativity considers motion in four-dimensional space-time.

In the four-dimensional world the shortest distances differ less from a straight line than might appear judging by planetary orbits. In one orbit around the sun, the earth's position in the world changes in time by the distance of one year. To express this distance in kilometres the laws of special relativity require the speed of light to be multiplied

by the number of seconds in a year. The result is a number 31,000 times greater than the diameter of the earth's orbit. Thus the earth's path through the universe is a helical line with a huge pitch-to-radius ratio. Such a helix comes very close to a straight line drawn through its ends. For the more distant planets the curvature of the helix is even less and the world out there is less warped.

Thus, to explain gravity as a change in the properties of space accelerated motion had to be made a special case of curvilinear motion. For this, time had to be made one of the dimensions of space, which was achieved by the special theory of relativity.

Hermann Minkowski interpreted special relativity as the fusion of conventional space and time in a unified four-dimensional superspace or, as we have already called it, space-time. In superspace the three spatial dimensions (x, y, z) are expressed in real numbers and the fourth dimension, time, is an imaginary number multiplied by the speed of light.

The time axis is thus distended, which is why relativistic effects are observable only at velocities comparable with the speed of light. A change of reference frame can be expressed as its rotation in four-dimensional space. The speed of light remains constant in this transformation, the conventional length changes (relativistic contraction), and time changes (this effect hardly needs to be discussed as there is probably not a single work of science fiction which doesn't mention it). But the so-called interval—the four-dimensional distance—between the events does not change.

Thus, the curvature of four-dimensional space fully explains all the effects of gravitation. The reader will have observed the difference between special and general relativity. The former studies the motions of bodies in planar space-time, the latter in curved. It could be called, as suggested by academician V. A. Fock, gravitational theory.

Gravity manifests itself as the effect of bodies on the properties of space-time, changing the properties and bending it. Space-time is no longer "absolute mathematical" space but a concrete physical entity described by non-Euclidean geometry.

Depending on the density of matter, that is, on its mass, the geometry of space-time may approach Euclidean, Lobachevski, or spherical geometry.

In the language of physicists space-time, or rather its physical properties, is expressed in terms of a complex mathematical quantity called a fundamental metric tensor.

MODELS OF THE UNIVERSE

The concept of curved space has had a profound impact on the most diverse fields of science. It has provided a basis for interesting, though by no means indubitable, ideas concerning the geometric properties of the universe. The first attempt to extend relativity theory to the whole universe was made by Einstein himself. He went out to establish how much local clots of matter warp the world.

The computations required data on the density of matter in the universe. It must be said that to this day problems concerning the curvature of space have been theoretically illumined only for the simplest case of uniform distribution of matter throughout space.

Newtonian mechanics applied to infinite space uniformly filled with matter requires an infinite force of gravity. This is meaningless, hence Newtonian mechanics cannot be applied to this case.

Einstein chose the simplest case of matter evenly distributed throughout the universe without voids or condensations. At first glance this seems to contradict all our experience and knowledge of the universe, which we commonly regard as being highly nonhomogeneous. Practically all matter is concentrated in stars, which are separated by vast distances. The density of interstellar space is negligible, being filled as it is with highly rarified cosmic gas and dust. Thousands of millions of stars form stellar clusters or galaxies, separated by even greater distances, measuring millions of light-years.

Einstein, of course, knew all this, but he reasoned on a much grander scale than galactic and intergalactic domains, when it is meaningless to speak of nonhomogeneous distribution of matter. After all, when we take a metal ball we do not think of it as being spongelike, which it actually is. But the distances between electron shells and nuclei, interatomic and intermolecular distances are so small that on our marcoscopic scale we regard the ball as solid.

In exactly the same way, on a supergalactic scale the universe may appear to be solid, and the greater the domains

considered the more evenly can the distribution of matter in them appear.

This reasoning also made it possible to assume the world to possess uniform curvature. True, it might seem strange to speak of the curvature of the world: on the one hand it is claimed that the world is infinite, on the other it is said that it is uniformly curved and hence must have a radius. When a contradiction appears one must always seek a new quality. When we speak of curved space we must draw a distinction between "infinite" and "endless" or "limitless". To continue our analogy with two-dimensional space, if our elastic surface, which we can also imagine to be extended infinitely in all directions, is made to have the same curvature at every point it can, as a result, bend into a sphere. But the surface of a sphere is closed, and though it has no boundaries it is of finite size. The surface of a sphere has uniform positive curvature, which is to say that it is equally convex at every point. This geometry constitutes the metric of closed three-dimensional space, of which it can be said that it is endless but finite. Another equally valid geometry is possible based on uniform negative curvature. The space it describes is saddle-like (Lobachevski's space) and is both endless and infinite.

In 1922, Alexander A. Friedman, a Leningrad mathematician, used Einstein's gravitational theory to construct two equally valid models of an endless universe uniformly filled with matter. His closed model is analogous to a spherical surface, the open one, to a saddle-like surface with uniform negative curvature. One may well ask how the infinite universe can be described by two such different models. Certainly, it is hard to represent a static, unchanging universe by two models. But it can readily be done with a dynamic, continuously changing one. Friedman showed that there is no such thing as an unchanging world. The curvature of space is continuously changing, because the density of matter is continuously changing. And which of the two models is valid within a given time interval is dependent solely on the density of matter. If it exceeds 10 protons per cubic metre then space is closed in a hypersphere; if not, the open model holds true.

Scientists, of course, set out to estimate the average density of matter in the observable, or astronomical, as it is also called, universe. Unfortunately, the universe seems

to be doing its best to thwart their attempts, for the mean density lies very close to the boundary value of 10 protons per cubic metre. If this is true for the whole universe, and so far we have no reason to doubt it, then we are incapable of deciding whether it is closed or open.

It may appear that we have once again landed into a theoretical impasse—and we have, only more so. To begin with, our basic assumption of uniform density was purely speculative and the true geometry of the universe may prove to be infinitely complex.

One of the most paradoxical properties of Friedman's models is that all the distances between the bodies in them must change with time. Space pulsates, alternately expanding and contracting. This is easily visualized on the closed model. Its two-dimensional analogue is a round balloon which can be blown out or deflated. If there are two-dimensional beings on its surface, when it is inflated all points will seem to them to be receding, "fleeing". This corresponds to a continuous reduction of the curvature of the world. As the curvature decreases so does the density of matter, which disperses, flees in all directions. Let us examine this in greater detail.

When a sound source is moving its pitch, as it reaches our ears, differs from the pitch of a stationary source. When a train appears in the distance and hoots as it approaches, the hoot seems piercing and high-pitched. As the train draws closer the pitch decreases, and when it rushes by the hoot becomes deeper and more muffled.

A similar thing is observed in the radiation spectrum of a moving light source. In this case the spectral lines are shifted from the positions they occupied when the source was stationary. An examination of the shift in the spectra of stars provides information as to whether they are receding or approaching and, moreover, their velocity with respect to us.

The phenomenon, which is connected with the well-known Doppler effect, is easily explained. When a source recedes the light waves reach a stationary observer at rarer intervals; when it is approaching the intervals are more frequent. In the former case the spectrum is moved toward the longer waves, the "red shift"; in the latter it is moved to the shorter waves: the "violet shift".

In 1919, the English astronomer V. M. Slipher made a

discovery which led to an entirely new notion of the universe. His measurements of the red shifts of a number of nebulae, which had previously been thought to be located within our Galaxy, indicated that they are receding from us at a remarkable speed: up to 1,800 kilometres per second. E. R. Hubble in America soon established that these nebulae were in fact stellar systems and proceeded to measure their distances from us.

By 1926, Hubble had not only established that these nenulae lie as far as 20 million light-years away but also that they appeared to be receding at velocities in proportion to their distances. He predicted that, accordingly, the more distant galaxies should display a greater red shift. To verify this, Hubble's co-worker M. L. Humason embarked on an extensive series of spectral analysis of remote galaxies with the aid of the 100-inch reflector telescope at Mt. Wilson. The dim, remote galaxies could not be resolved into individual bright stars and the distances to them had to be judged from the brightness of the galaxy as a whole. In other words, it was accepted that a galaxy that appeared one-quarter as bright as another was twice as far. Of course, individual galaxies might well deviate from the rule, but the totality of galaxies could be expected to follow it. This principle remains fundamental in determining astronomical distances to this day.

Humason obtained his first really marked red shift in 1928 in studying the spectrum of galaxy NGC 7619. Hubble predicted that its velocity should be somewhat under 4,000 km per sec. This was brilliantly confirmed when Humason came up with the figure 3,800.

In 1936, American astrophysicists exploiting their telescope's possibilities to the utmost studied a cluster of galaxies in Ursa Major and established that they were travelling at about 40,000 km per sec.

At distances exceeding 500,000,000 light-years the speeds of galaxies were found to be in direct proportion to the distance from us. In a sense this discovery was disappointing, as cosmologists had been hoping to discover some changes in the ratio as they penetrated deeper into the universe. Further probing of the universe had to await completion of the 200-inch telescope at Mt. Palomar.

In 1951 the red-shift research programme was continued with the help of a new high-speed spectrograph. The spect-

rum produced by it on a photographic plate is a strip only five millimetres long, yet it is sufficient to measure the red shift to an error of less than one-half of one per cent.

Humason measured the red shifts for remote galaxies receding from us at a speed of 65,000 km per sec. What did he find?

Eighteen of the dimmest groups of galaxies are fleeing from us at a velocity proportional to their distance. The dependence is strictly linear. The remotest groups, however, display deviations from the linear law. These galaxies, lying some 1,000 million light-years away, are in fact receding at a speed 10,000 km per sec greater than they should have according to the linear law.

Some astrophysicists have concluded from this that 1,000 million years ago the universe was expanding faster than it is now. If the measurements and the conclusions are correct this would mean that we are living in a developing universe, not a stable one.

We are now also able to judge of the average density of matter throughout the universe. The rate of slowing down of expansion depends on the mean density of matter: the higher that density the greater the retardation. Based on the deviation from the linear law it is possible to calculate that the average density is of the order of 3×10^{-28} gram per cubic centimetre, or one atom of hydrogen per 5 litres.

Proceeding from this data it becomes possible to speak seriously of the geometry and curvature of the universe. It will be remembered that we have three basic models: straight, open, infinite Euclidean space; curved, closed, finite space (like the surface of a sphere); curved, open, infinite space (like a saddle surface).

THE PRIMEVAL ATOM AND BALLOON UNIVERSE

We can now go back to consider Friedman's models. To begin with, the surface of a sphere has no centre, hence any two-dimensional being can claim with equal right that he is at the centre of the universe and all the rest are "fleeing" from him. Accordingly, to an observer in one of the galaxies mentioned in the previous chapter our Galaxy will also appear to be fleeing.

Does the curved-space theory mean that the world is

finite? We have seen that the question is invalid since the closed model is but one of two based on the uniform distribution concept. If we reject this arbitrary idea the possibilities for investigation become truly limitless.

Saying that the world is finite does not imply that it is limited, only that it is impossible to determine an infinitely great distance. This does not contradict the premises of dialectical materialism, which proceed from the notion that the world is infinite in both space and time. All the more so as the latest cosmological data on the mean density of matter in the universe tend to the conclusion of a world not limited in space. But in all cases it works out that there is a finite time interval of 10,000 million to 12,000 million years at the beginning of which the density was infinite. Does this mean the beginning of the world? We shall answer this question a little later when we discuss the evolution of stars.

Meanwhile, a few words on the conclusions that were drawn immediately after the discovery of the expanding universe. They demonstrate how far one can go when one wrongly applies and interprets correct theoretical propositions and the results of objective experience.

The nineteen-thirties was a time of fierce debate in which many a theoretical concept collapsed. The main arguments centred around the expanding universe hypothesis. Some astrophysicists began by attempting to explain the red shift without resorting to the idea of fleeing galaxies. "Something happens to the light quantum on the way and it reddens," wrote the Dutch astronomer W. de Sitter. What is this "something"? It has been suggested that in its wanderings through the infinite expanses of the universe a photon simply grows older. Hopes were placed on interstellar media and magnetic fields which could affect light in some ways. But what? There are no experimental data to confirm the "ageing" or "fatigueing" of quanta, and it is not surprising therefore that the view that the world is really expanding soon came to be shared almost universally. But why is it expanding?

The expanding universe theory quite naturally revived thoughts of the creation of the world. Leading among the exponents of this idea were the Belgian abbé G. Lemaitre and the celebrated English physicist A. S. Eddington, whose religious-mystical views came to dominate his thinking

in his latter years. Initially the reasoning of the new-fangled creationists did not arouse opposition. Proceeding from the observed fact of the expanding universe, one is entitled to conclude that, going back in time, it must have been smaller in size, and if we go back far enough we can come to a time when the radius of the universe was zero—or almost, since for obvious reasons it couldn't be zero. Hence, one can assume that that moment marked the beginning of the universe.

Calculating from the observed expansion velocities, one can conclude that the "moment of creation" occurred several thousand million years ago. In Lemaitre's view that was when the "primeval atom" exploded to create the universe with all its stars, planets, atoms and elementary particles.

In a letter to a Quaker society Eddington once wrote that its members would hardly reject a scientific explanation of the creation which could perhaps glorify God more than the traditional Biblical account. Those who wished, as it were, to sanctify the discoveries of science by declaring them to be additional indications of God's omnipotence could be understood, but their position irritated scientists who saw it as an attempt to restrict their spirit of free investigation to one type of explanation.

Eddington's position was supported by his compatriot Milne, even though he expounded the infinite world concept. For, he declared, it took a much greater God to create an infinite universe than a finite one.

Thus, two distinguished researchers proceeding from two apparently different positions arrived at the same fallacious idea.

It would seem that there is no need to discuss the views of Lemaitre or Eddington. Just as patent offices all over the world refuse to consider designs of perpetual motion machines, so we atheists can forthrightly reject any theory based on the assumption of divine creation. Still, we are entitled, nay, in duty bound, to discuss the purely formal aspect, the logical and mathematical apparatus of the theory. Especially so as its rational germ has been adopted by modern concepts of the evolution of the universe.

The mathematical theories employed by Lemaitre and Eddington do not necessarily lead to the conclusion that the expansion of the universe should continue eternally

or that it must have begun after an initial state of rest. As shown by de Sitter, from the mathematical point of view Lemaitre's theory is one of several possible solutions to the problem of the expanding universe. There are many other solutions, all of which can be justified by facts. According to one, the universe will always be in a state of expansion; but several thousand million years ago it was of some minimal size, following an epoch of compression of an infinitely dispersed medium. According to another, not very original, theory, which does away with the unusual state of matter prior to the present expansion, the universe is pulsating, alternately expanding and contracting. Several thousand million years ago its radius was minimal, since then it has been expanding, and this expansion will cease after a certain maximum is achieved, when contraction will set in again. The cycle we are living in is one of an infinite number of similar cycles.

Thus Lemaitre's God, whether intentionally or not, turns out to be no more than an onlooker, since the "beginning" is just one stage in the evolution of the universe.

The pulsating universe theory makes no mention of any initial motion starting from rest at the creation of the world or of the spewing of matter in all directions following the explosion of a "primeval atom". The author of this theory, Tolman, an American specialist in thermodynamics and relativity theory (and one of the makers of the first atomic bomb), wrote that there is no reason to assume that the universe was ever created at some specific moment in the past.

If Lemaitre and Eddington had been materialists they would never have "deduced" God from their reasoning: he simply doesn't derive logically from it. Moreover, they would probably have come to the conclusion of the possibility of an alternately contracting and expanding universe. But—and this is most graphic proof of the limitations of a science that is based on positions of idealism—they preferred to turn to God.

In the past the pulsating universe idea has been severely, and often unjustifiably, criticized. Today the ranks of its supporters are growing. True, in the course of its evolution it has undergone certain changes, including new interpretations of the expansion and contraction processes. In fact, one could say it has become a new theory in old wrapping.

In connection with this theory the American astrophysicist A. R. Sandadge remarked that if, as our data seem to indicate, the expansion of the universe is slowing down, it will evidently halt one day and be followed by a contraction, and if after that the matter of the universe returns to its initial super-dense state and explodes again, in another 15,000 million years humanity will again be tackling the same problems.

Many theories purporting to explain the expanding universe have been advanced and new ones are continuing to appear. Yet the more theories there are the more contradictions there seem to be. And these give rise to new hypotheses which attempt to cope with the hundreds of facts accumulated by science.

Unfortunately, the authors of some of these hypotheses could do well to learn objectivity even from such subjectivists as Lemaitre and Eddington.

In an attempt to escape the contradictions arising from the different ages of celestial bodies and the picture of an increasingly diluted universe, the English astronomer Fred Hoyle created a model of an expanding universe in which the average density remains unchanged. Hoyle felt compelled to reject the notions of a finite and endless space and an initial "starting moment" and returned to the idea of the world as infinite in time and space. Thus, Hoyle's basic assumptions are legitimate and at least no more arguable than any others.

But he also had to assume that the matter leaving a given spatial domain is continuously being replaced by new matter appearing out of nowhere and from which new galaxies are being created. This assumption could be acceptable if only Hoyle could say where the new matter came from. His views on this score, however, leave no place for doubt.

People, he wrote in 1952, keep asking where matter comes from. The answer was, he declared, from nowhere. It just appears ready-made. At some given moment the different atoms constituting matter do not exist, then at the next moment they do exist. Although this might seem strange, he said, it was perhaps no stranger than any other concept of the creation. Other theories, he pointed out, assumed that at some given moment all the matter of the universe had appeared in some titanic explosion. This, in

his view, was in fact harder to believe than the idea of continuous creation.

The subjective nature of this reasoning is much more pronounced than in all the works of Eddington.

The rate of Hoyle's "continuous creation" is small: one atom per year within a volume equal to London's St. Paul's Cathedral. But even this low productivity of the divine machine is sufficient to "save" the world from the rarefaction of matter caused by the fleeing galaxies.

Other leading scientists have also toyed with the continuous creation, or steady state, idea unable to resist the temptation of adopting the "simplest course" and interpreting the stranger points of their theories as properties of nature.

Thus, Ernst Pascual Jordan, proceeding from purely abstract, formal considerations regarding integral-number relationships between world constants, decided that matter is created by the potential energy of the universe concentrated in supergiant stars.

The Englishmen H. Bondi and T. Gold also placed great hopes in the energy of world space. But before setting forth their views we must get acquainted with some new properties of physical space-time.

THE REMARKABLE POPULATION OF VACUUM

The discovery of the positron and transmutations of particles and photons was one of the greatest achievements of relativistic electron quantum mechanics and quantum electrodynamics. But the assault on the secrets of the atomic nucleus had served to distract physicists' attention from the electron-positron theory for a whole decade, invoking it only in considering nuclear processes such, for example, as beta decay.

Quantum electrodynamics had seemed to reach an impasse. This notion was greatly facilitated by the difficulties physicists had encountered in field theory.

Then, in 1947, certain electron effects discovered in the hydrogen atom caused some stir in quantum electrodynamics. According to Dirac's theory, two energy levels in the hydrogen atom should coincide. However, Lamb and Retherford, two young workers of Professor I. I. Rabi's laboratory at Columbia University, carried out a series of

subtle radiospectroscopic experiments in which they established that these electron energy levels form a slight shift corresponding to a radiation wavelength of around 21 cm emitted by atoms.

Soon the cause of the shift effect was discovered. It turned out that the electron interacts not only with the real external Coulomb field of the proton or other external fields, but with random oscillations or fluctuations of the "vacuum" electromagnetic field. It is no longer correct to speak of vacuum as an absolute void. It does represent the lowest electrical state of a system whose average electromagnetic field is zero. However, fluctuations appear in vacuum which give electrons an increment of kinetic energy. This additional energy, taken from a "void", reduces the electron's attraction to the proton, which accounts for the upward shift in energy levels.

The explanation of the Lamb shift represented, in effect, a discovery of peculiar types of interaction between particles and the vacuum state of the quantized electromagnetic field.

It could be noted that the shift was discovered, rather hesitatingly, before World War II, but, in the absence of an adequate theoretical explanation, largely ignored.

It would appear that such a delicate, typically subatomic effect, could be of interest to only a small number of narrow specialists. In reality though, the 21 cm radiation has provided man with some of the most valuable information he has ever obtained about an entirely different world, the world of galaxies.

The first man to note the phenomenon was a Dutch student by the name of Van de Hulst, who showed in 1944 that atoms of hydrogen dispersed throughout space can radiate radio waves in the 21 cm wavelength.

In 1948, the Soviet astrophysicist I. S. Shklovsky, an expert in radioastronomy, provided an elaborate and beautiful theory to back up Hulst's ideas and outlined ways in which it could be verified experimentally.

Shklovsky's theoretical postulates were brilliantly confirmed three years later when radio-frequency radiation from neutral cosmic hydrogen was discovered. Vast tenuous clouds of hydrogen envelop the spiral arms of our Galaxy, and it can be found in other stellar systems as well.

That is why radio observations on the 21 cm wavelength have provided a tool for studying the structure of galaxies and probing into their cores. Within a few years radio waves have helped to reveal more mysteries of outer space than visible light did over the last several centuries.

Investigations reveal that radiation in the 21 cm wavelength is extremely widespread throughout the universe, which enabled American astrophysicists Kokkoonni and Morrison to postulate in 1960 that, if there are intelligent beings anywhere in the universe (and today hardly anyone denies this), they would surely take note of this behaviour of cosmic hydrogen, so different from the continuous radio-frequency radiation spectrum of galaxies and stars. The chance cannot be ruled out that at this very moment some learned scholar on a planet revolving around Tau Ceti or Alpha Centauri is observing these very waves.

But let us return to the properties of vacuum.

As the reader recalls, the foundations of the theory of vacuum were laid by Dirac. It was, however, only after the discovery of the Lamb shift that the correct conclusions were drawn from Dirac's original and daring notions concerning the nature of vacuum.

As has often been the case in the history of physics, the mathematical formalism had been elaborated in considerable detail. All that was lacking was a single link to bridge the gap over the unknown. This link was filled by the concept of the new physical properties of vacuum. It could take root, however, only through experiment, although the optically discovered level shift could have been predicted theoretically a decade earlier.

That is one of the reasons why erroneous attempts had been made in theoretical physics to exclude zero electromagnetic fluctuations of the vacuum (photons), as well as electron-positron fields, from the theory as unobservable and leading to infinite values for various quantities.

The physical properties of real space are not restricted to the ability to curve and thus transmit gravitational field. Electromagnetic forces are as important to physics as gravitational.

Classical physics attained its summit with Maxwell's theory, which showed that light and similar radiation can be treated as electromagnetic waves. Faraday and Maxwell introduced the concept of field into physics and showed

that electromagnetic interactions and radiations are manifestations of field properties.

It was only natural to ask: Is there such a thing as space without fields? Classical physics, which considered the "absolute mathematical" properties of space separately from physical field, replied in the affirmative.

Quantum physics yielded diametrically opposed notions.

Rayleigh and Jeans calculated the degrees of freedom of radiation confined in a given spatial volume. When the volume is limited the problem is reduced to that of an ordinary resonant cavity. A resonant cavity possesses a great number of resonance or natural frequencies. To each natural frequency within the cavity's volume corresponds a large number of oscillations of different kind.

Every degree of freedom of radiation represents a certain type of electromagnetic oscillations which can be excited to one degree or another.

To make this more understandable, imagine every unit volume of space filled with a definite number of oscillators. Every degree of freedom or, to be more precise, every type of electromagnetic oscillations, can be called a field oscillator.

Every resonant cavity for each given particle possesses a certain number of field oscillators. If space is endless it can be characterized in terms of oscillator density per unit volume. This density is derived from the Rayleigh-Jeans formula.

Thus, space revealed itself to be a reservoir of electromagnetic radiation. This was most unexpected and well nigh incredible. It overthrew all previous notions. It had always been taken for granted that radiation is emitted by concrete bodies. Yet here was empty space filled with electromagnetism.

If space and a body are in contact for a sufficient period of time thermal equilibrium must eventually establish between them. In the process every oscillator acquires additional energy which can be transmitted only by quanta.

When quantum theory was finally formulated one extremely interesting aspect came to light. It was found that, in addition to the integral number of quanta an oscillator can receive or emit, it always retains a residual half-quantum of energy which cannot be taken away. This is the zero energy of the Lamb shift.

Even at absolute zero temperature, when it would appear that an oscillator has no energy reserve whatsoever, it continues to perform zero oscillations. These oscillations are an intrinsic property of vacuum. Oscillators are quantum carriers and any oscillator can receive or give off any integral number of quanta.

Classical physics treated matter as an active radiator, and space as an empty and passive receiver of radiation, which vanished in it without a trace. Quantum physics explained the existence of stationary electron states. But to explain the emission of radiation by an excited atom it was necessary to take external effects into account. According to the quantum theory of radiation these effects come from field oscillators. If there are photons in the surrounding medium they can act on an atom and make it emit radiation. This is the forced, or induced, excitation on which laser action is based.

An excited atom, however, is capable of radiating in absolutely empty space even in the absence of photons. This is spontaneous radiation caused by interaction with the zero oscillation of vacuum.

It is not surprising therefore that the mathematical equations of the quantum theory of radiation equally take into account photon density and oscillator density. Thus, free oscillators are as it were a reserve of unborn but possible photons, a storehouse of virtual quanta.

FOSTER PARTICLES, FROM THE PHYSICO-LEGAL ASPECT

The notion of temperature is naturally associated in our minds with matter. However, in making the acquaintance of physical vacuum we can depart from such traditional, not to say dogmatic, concepts. More, we must even be prepared to accept such an apparent absurdity as the temperature of vacuum.

How, it would seem, can one discuss temperature in vacuum, where there is not a real atom of matter? But vacuum is pervaded with electromagnetic waves, and if that is the case why not extend the temperature concept to photons? To be sure, photons are the least particle-like of elementary particles. Ordinary corpuscles of matter readily exchange energy in collisions. As a result energy is quickly distributed among them according to Maxwell's

law, which is to say that it becomes thermal energy. Photons, on the other hand, interact very weakly and, unlike matter, radiation may not have a definite temperature.

If, however, radiation is in thermodynamic equilibrium with matter it acquires the latter's temperature. This is what is known as equilibrium, or thermal, radiation. This invisible infrared radiation is emitted by all bodies about us, and by ourselves, of course.

In many ways this radiation is like a gas. Like a gas, it exerts pressure on surrounding objects. The pressure of the "photon gas" can be measured. It is ubiquitous, this gas, which is continuously spewed into space by all the stars in the skies. If we attempt, in a thought experiment, to screen a section of the vacuum from the photon gas we immediately come up against insurmountable difficulties. First of all, we must encase a section of space in some substance impermeable to matter and light. But we immediately observe that the vessel itself radiates heat, thus contaminating our ideal vacuum. To get rid of this radiation the vessel must be cooled to absolute zero. But according to the third law of thermodynamics, this is impossible. It is not for nothing that the name proper "physical vacuum" is applied to space filled with equilibrium thermal radiation. And not only with it. As we know, physical vacuum is pervaded with quanta of other fields in addition to the photon gas. But we have returned to the vacuum not for its sake alone. We need it for an analogy.

Besides the known particles which enjoy full citizenship rights, there exist, at least in scientific nomenclature if not in the real world, so-called quasiparticles. They perform an honourable role but their fate is unenviable. They, not the neutrino, truly deserve to be called ghost particles. The more the formal apparatus of quantum theory extends to the different phenomena the more "illegitimate" particles deprived of "civil" rights there appear. Or perhaps it would be more correct to say that these particles enjoy full rights as citizens even though they don't exist.

To begin with, let us make the acquaintance of the "particle" of sound. There is nothing extraordinary about this juxtaposition of words. The propagation of sound is a wave process and we are therefore fully entitled to apply the mathematical apparatus of quantum theory to it. Acoustic energy is also emitted in separate batches. But the

quantum nature of sound had so far been established only at very low temperatures, when matter possesses minimal energy reserves. The acoustic field quantum has been called a **phonon**.

An intriguing feature of standing sound waves is that in crystalline bodies they behave like a gas, or rather like the photon gas in vacuum. Only the frequency of light quanta is not limited whereas phonons possess a maximum frequency threshold. Phonons are incapable of carrying unlimited energy. Their energy is the thermal energy of a solid body. We can declare this, ignoring the fact that a body is constituted not of phonons but of molecules and atoms. Theory allows us to do so. It repays us for this departure from reality with excellent equations which can be used to compute very important properties of real bodies.

Such an approach is not due to a theoretician's whim, it is a sheer necessity. Without substituting phonons for atoms we cannot hope to gain an understanding of the random thermal motions of particles in crystals. A crystal can be treated as consisting of peacefully coexisting atoms and phonons: that is, it is made up of orderly positioned atoms, with the phonon field as the net result of all the interactions between them. To be sure, this coexistence is not one of equal partners, for phonons are inconceivable without atoms whereas atoms can get along fine without acoustic quanta.

In an interesting and witty article about quasiparticles, Professor D. A. Frank-Kamenetsky offered the following analogy to describe the relationship between particles and their "ghosts". "The difference between particles and quasiparticles", he wrote, "is something like the difference between a physical and juridical person. Society consists of people whom lawyers call physical persons. In social relations, however, one often has to deal with organizations, offices, firms: these are juridical persons. One cannot say that a juridical person is simply a collective of people, that it consists of physical persons. It substitutes for them, performs their functions, plays their part. It is often much easier to get to the core of a legal case by ignoring real people and reasoning only in terms of juridical persons (though this may not always be commendable). In a similar way, quasiparticles as it were substitute for 'real' parti-

cles and represent them. This is true if the particles are truly 'elementary', if they are primary building blocks of the universe. But quantum physics permits us to regard all particles as quanta of physical fields. If fields are the foundation of everything, all that is left for us to say is that particles are quanta of vacuum fields and quasiparticles are quanta of internal fields of matter, which is itself constituted of particles."

Now let us continue the comparison with gas and heat. Whereas in a gas every particle possesses some energy reserve, in a crystal the uncertainty of the atomic world becomes manifest. A crystal is an ensemble of particles in which a continuous redistribution of thermal energy is taking place. This energy is distributed not among individual particles, but among collective motions. Other energy distributions display similar characteristics, notably the energy of electron excitation, which migrates freely through the crystal like a nonviscous fluid through sand. This roving excitation can also be quantized. Ya. I. Frenkel called the quantum of excitation an **exciton.** The association of an exciton with the distortion of the crystal lattice caused by it can also be represented as a quasiparticle, which S. I. Pekar called a **polaron.**

Quasiparticles helped solve a problem of primary importance. They have been used to build up a theory of some of the most enigmatic processes. Suffice it to say that the unique properties of the quantized liquid, helium II, were explained on the basis of a gas comprizing audio phonons and "vortex rotons". This theory was enunciated by Lev Landau and won him a Nobel medal.

Even waves in plasma can be described in terms of the ubiquitous quasiparticles—**plasmons, helicons,** and what have you. And A. B. Migdal of the Soviet Academy of Sciences recently demonstrated that many properties of the atomic nucleus could be explained if it is regarded as a gas of quasiparticles.

One could speak of quasiparticles indefinitely. The important thing for us is to know that such things exist and that they possess a rather vague "juridical person" status. Deserving a closer acquaintance is another set of "doubtful" particles whose status is even more vague. Nothing prohibits their existence, but no one has ever observed them; theory has nothing against them, but experimen-

ters have yet to track them down. To balance the picture it could be added that some theoreticians hold that both nature and theory are better off without them.

GRAVITATION OF DREAMS AND REALITY

Yukawa's idea that all forces are the result of intermediary particle exchanges led to the prediction of one more new particle, the **graviton.** Gravitation acts at a distance. Like electrical force, its radius of action extends into infinity. Therefore the particles whose exchanges are to ensure the mutual attraction of bodies should not possess rest mass. Although gravitons have never been observed, physicists know many of their properties. Today they are at least as real as Yukawa's mesons before the discovery of pions or Pauli's neutrinos before Reines and Cowan's experiment, leaving the question of the existence of gravitational field quanta open.

The important thing for us is that the graviton must possess zero mass and, hence, propagate with the speed of light. For the absence of mass is equivalent to the absence of inertia, that is, the resistance a body offers to acceleration. That is why massless bodies must move with the greatest possible velocity, which is the speed of light.

In this connection one common error should be noted. It is rooted in a term which is more restricted than the phenomenon it describes. The maximum possible speed in nature is by no means intrinsically associated with light. This is the speed of any noninertial body. Simply, historically light happened to be the first noninertial substance studied by man. In actual fact we could speak with equal right of the propagation speed of gravitation or neutrinos as the limiting velocity.

In the forties and fifties physics tended to ignore problems of gravitation. It was a time when particles were coming thick and fast. Lately, however, interest in gravitation has begun to increase perceptibly. Confirmation of this can be found in the international conferences on gravitation held in the United States in 1957 and in Paris in 1959.

As is known, the science of gravitation was "born" together with Isaac Newton's law. Today it seems perfectly natural that two bodies are drawn toward each other with

a force that varies as their masses and inversely as the square of the distance between them.

True, neither Newton nor those who came after him could explain why this is so. For more than 200 years physicists had to make good with Newtons' law, until Albert Einstein came along with his general theory of relativity or, as it is often called, gravitational theory, theory of curved space. Mathematically the curved space theory had been worked out earlier by the Russian Nikolai Lobachevski, the Hungarian Johann Bolyai and the German Bernhard Riemann.

Lobachevski was convinced that real space must be curved, if only slightly. At the time, however, there were no astronomical means of testing the hypothesis: the great mathematician's prediction was shown to be true only one hundred years later.

During a solar eclipse it is possible to take pictures of stars lying close to the limb of the sun. Scientists undertook to determine the path light takes from such stars to the earth. If a change in a star's apparent position is observed it means the ray of light is drawn toward the sun and travels through curved space. This deflection was registered, and it amounted to approximately 2 seconds of arc. This negligible curvature brilliantly confirmed the theoretical predictions. Several years later space curvature was additionally confirmed by observations of the red shift in the spectra of superdense stars. The shift toward longer wavelengths is explained by the powerful gravitational field of these celestial bodies, one cubic centimetre of which weighs many tens of tons.

Until recently gravitation was neglected in atomic and nuclear theories. However, it may well be found that gravitational forces will also have to be invoked to explain the structure of elementary particles.

Contemporary physics requires a revision and refinement of various aspects of the theory of gravitation as enunciated by Einstein. Attempts are being made to establish individual elements of gravitational field or, in other words, to quantize the field and discover its connections with other forms of matter.

It was Einstein who discovered that weak gravitational fields propagate as waves at the speed of light. This means

that they can carry energy. It also means that a portion of the radiation must be dissipated in the process.

If a mass radiating gravitational waves is pictured as a kind of gravitational charge, the waves, then, can be quantized. Hence, just as electromagnetic field has photons and nuclear field has mesons, gravitational field must have quanta of its own—gravitons. Theory predicts a spin of 2 for gravitons.

Thus, we have an ultraweak interaction: gravitational. Now we can explain Newton's law. Gravitational attraction is effected through graviton exchange, perhaps similar to quanta exchanges in electromagnetic and nuclear fields. In that case, according to quantum mechanics, gravitons should transmute into photons and other particles and back again: in particle annihilation gravitons should be produced along with photons and mesons.

These theoretical concepts are expounded by the leading Soviet physicist D. D. Ivanenko. But there are very many physicists who refuse to "allow" gravitons into the microworld.

As always, the final word rests with experiment.

A legitimate question is how gravitons can be expected to behave in a world of antiparticles: will it perhaps have antigravity instead of gravity?

At an international congress on elementary particles held in Padua in 1957, Emilio Segre asked: "Will not antiprotons fly up instead of falling down?"

An indirect answer to this question is provided by the old test of the deflection of light rays during a solar eclipse. The thing is that a quantum of light is at one and the same time a particle and an antiparticle. So if gravity affects it then, evidently gravity does not distinguish between particles and antiparticles. According to Einstein's theory, from the gravitational point of view particles and antiparticles must behave in the same way.

Let us try and compare gravity and electricity. We know numerous macroscopic manifestations of electricity. In such phenomena as lightning, power transmission by wire or, for that matter, television, quantum properties play a negligible part. In the microworld, on the other hand, they are of primary importance. Suffice it to recall that it is electrical forces which determine an atom's stability. The photon exerts its influence over a sufficiently

wide area. Gravitation, however, manifests itself only in the macroscopic world. And this is not surprising. As mentioned above, gravitational forces are extremely weak, weaker than the weakest interactions. The gravitational attraction between an electron and a proton is less than their electrical interaction by forty orders of magnitude.

But once it escapes from the confines of the microworld into galactic expanses the weakest of the weak becomes the primary of the foremost. The first to give up in the rivalry with gravity are strong and weak interactions, which dwindle to nothing over distances exceeding 10^{-13} cm. To be sure, electricity, like gravity, lays claims to distant action. And though electric forces decrease as the square of the distance, they compare successfully with the almost instantaneous disappearance of nuclear forces. That is why in principle electricity would have been in a suitable condition to overcome gravitation on the cosmic battle field, if not for the fact that planets and stars are generally electrically neutral. Which clears the way for gravity and the law of universal gravitation.

To be sure, the old Newtonian theory should be treated rather as "gravistatics". Just as electrostatics treats only of resting masses and constant electrical fields, so gravistatics dealt with an unchanging gravitational field.

The question of whether an interaction can be transmitted instantaneously, which had once worried physicists, has long since been resolved. The prohibition of velocities exceeding 300,000 km per sec introduced by Einstein holds for gravitation. We also know that gravitation is a manifestation of space curvature. The change in curvature from one point to another can be likened to a wave process—the gravitational waves predicted by Einstein, which still remain a hypothetical conjecture. Let us try to trace an analogy between gravitational and radio waves.

Electromagnetic waves were also first predicted theoretically, in the eighteen-sixties. Almost twenty years passed before Hertz succeeded in reproducing the waves predicted by Maxwell in laboratory conditions. More time passed before Alexander Popov and then Guglielmo Marconi sent their first wireless telegraph messages. The scheme is on the whole fairly typical and boils down to three stages: theoretical prediction—experimental verification—practical application. Gravitational waves are still in the first link

of this magic chain. Nevertheless, many leading theoreticians do not doubt that they do in fact exist.

What are the obstacles to the experimental detection of these waves? This has been mentioned above. It is a case of an extremely weak signal due to the very small value of the constant of gravitation.

The energy of waves increases with the mass of the oscillating body and the oscillation frequency. But double stars, for example, which have tremendous mass, have a negligible oscillation frequency, while elementary particles, with their tremendous frequencies, possess negligible mass. As a result, whatever body we take as a gravitational wave generator the effect is too weak to be picked up by our hypothetical instruments.

Take for example the giant planet Jupiter. It can be calculated that the power of the gravitational radiation generated by it in its rotation around the sun does not exceed 450 watts—as much as the power of a small electric toaster.

Nevertheless, scientists hope to solve the problem of artificially generating an observable gravitational field. For this it is necessary, first of all, to make a body oscillate at a frequency which would make the energy of the radiated gravitational waves commensurate with the sensitivity of the recording instruments.

The formula of relativity theory which determines gravitational wave intensity seems promising enough, since it includes the oscillation frequency raised to the sixth power. This means that if the frequency is increased by only one order of magnitude the intensity must increase a millionfold. However, calculations carried out in the forties by Eddington dashed the optimistic hopes. The radiation power of a rod one metre long is of the order of 10^{-30} erg per sec, with no possibility of increasing this vanishingly small quantity in any way. The speed of rotation cannot be increased indefinitely owing to centrifugal force, which builds up to a point where it destroys the rod. Thus the strength of the materials sets a limit to the speed of rotation and, hence, the intensity of the gravitational radiation.

Recent years have seen tremendous advances in physics, electronics, automation. Today laser amplifiers are used to detect signals which only a few years ago would have see-

med hopelessly weak. This has, naturally enough, revived hopes of at last detecting gravitational waves.

The American scientist John Weber was the first to carry out the necessary technical calculations for a gravitational generator and detector employing a piezoelectric crystal.

Gravitational waves reaching the crystal should cause a certain deformation in it, which in turn must cause a degree of electrical polarization. The resulting potential difference can be detected with the help of highly sensitive electrical instruments of conventional design.

The crystal can also be used as a generator of gravitational waves. For this it must be made to oscillate with the help of a high-frequency electrical field. To be sure, in this case, too, one must reckon with the fact that if the oscillation amplitude passes a certain limit the crystal will simply disintegrate.

Calculations reveal that a piezoelectric crystal 50 cubic metres in size could radiate gravitational waves of no more than around 10^{-13} erg per sec intensity. Working as a detector it could pick up waves of the order of 10^{-3} erg per sec. Thus, the transmitter in Weber's calculations is too weak for any existing instruments to pick up its radiation. However, this did not discourage him. Weber and his associates hope to detect gravitational waves from the sun or domains of interstellar space.

Moscow physicists V. B. Braginsky and G. I. Rukman suggest taking two parallel cylindrical banks of piezoelectric crystals. Each crystal is a lamina of barium titanate one square metre in area, and each bank consists of 20,000 such crystals. The two banks are aligned as close as possible and isolated to keep any electromagnetic or acoustic waves from passing between them.

If the two banks are now made to oscillate, the only interaction between them will be gravitational as there is no insulation capable of halting the weak but all-penetrating force. If the oscillation phases of the laminas are in step, then, according to the laws of resonance, which govern electrical waves, the intensity of the system's gravitational radiation will be four times that of a single bank. If the oscillations are out of step they will cancel out.

When the phases are in step a certain increment of electrical power input will be required to maintain the oscilla-

tion amplitude of the crystals to make up for the very small portion expended on the excitation of gravitational waves. It is this power increment that Braginsky and Rukman suggest measuring. Calculations show that at a frequency of 10^6 hertz and a power expenditure of around one million watts the signal to be measured must be extremely weak: of the order of 10^{-25} watt.

Now note that our native planet not only radiates gravitational waves but receives them from space as well; that is to say, it acts as a gravity antenna. If that is the case the incoming waves should affect the earth's behaviour in some way or other.

Paul Dirac expressed the idea not so long ago that astronomical anomalies in the earth's rotation, such as the irregular axial rotation responsible for fluctuations in the length of the day, may be due to gravitational wave pulses reaching the planet. A careful study of the globe's oscillations could sooner or later enable us to sort out the different types of oscillation and isolate those due to gravitational waves; these could then be studied to determine the intensity of the waves.

And one more consideration.

Up till now we have been continuously emphasizing the negligible intensity of gravitational waves. Even binary star systems radiate them in very small quantities. It should, however, be remembered that these waves have been radiated for thousands of millions of years. Every oscillation, every rotation continuously generates them. Thanks to this, the total amount of gravitational radiation in the universe is continuously increasing. Furthermore, gravitational waves of appreciable intensity may be emitted in explosions of supernovae and other astronomical cataclysms, such as the birth or collision of galaxies and stars.

The American scientist J. Wheeler considers that the density of the energy (or equivalent mass) of gravitational waves in the universe should be approximately 10^{-30} gram per cubic centimetre of space.

A negligible quantity, to be sure, yet it is of the same order as the density of the energy (or the equivalent mass) of all the visible matter in the shape of stars, planets, cosmic dust, etc.

In this connection it is interesting to note that not long ago Soviet physicists B. M. Pontecorvo and Ya. A. Smoro-

dinsky at Dubna and V. M. Kharitonov at Yerevan undertook to assess the density of neutrinos in the universe. They arrived at some remarkable conclusions. These extremely elusive particles which hardly interact with matter and are capable of passing unmolested all through the earth must have accumulated in vast numbers over the millennia. Their density is also approximately equal to that of all visible matter. (To explain this, it should be recalled that in the thermonuclear reactions going on in the sun about 10 per cent of the total energy is emitted as neutrinos and is thus spewed into the universe together with light.)

All these estimates (which are very approximate) seem to indicate that the total energy of all "conventional" types of matter in our universe amounts to only about one-third or one-half the total energy reserve. The balance is accounted for by neutrinos and, possibly, gravitational waves.

In 1959, Paul Dirac put forward the bold hypothesis that the graviton may be made up of a neutrino pair. At least, some facts indicated the possibility, notably the computed graviton spin, which Dirac found to be 2. As the neutrino's spin is 1, it seemed very tempting to regard the graviton as the product of a fusion of two neutrinos. Additional confirmation of this possibility is the neutrino's remarkable penetrating ability.

It has been mentioned above that gravity is a force 10^{40} times weaker than electrical interactions. Dirac launched a search for a physical quantity corresponding to this ratio, and he found that the age of the universe expressed in "nuclear units of time" agrees with it. The time light needs to run the diameter of a nucleon is 10^{-23} sec. This is the nuclear unit of time, in terms of which the age of the universe is 10^{40}. A remarkable coincidence, isn't it: the ratio of electrical to gravitational interaction can be measured in terms of the age of the universe.

In view of the fact that electrical activity does not change as the universe ages, Dirac came to the conclusion that gravity must decrease with time. For if the ratio of electrical to gravitational interaction, which is equal to the age of "our" part of the universe, is always increasing while the numerator remains constant, then, apparently, the denominator, i.e., gravitation, must decrease with time. If that is so then the universe must expand with time.

Another consequence of diminishing gravitation should be an expanding earth. Although this has not yet been conclusively proved, some physicists claim that the earth's radius is increasing at a rate of about 0.5 millimetre per year.

Nowadays science is advancing at an unprecedented rate, so this hypothesis may soon be reliably confirmed scientifically.

AND NOW THE MONOPOLE

More than 30 years have passed since Dirac suggested that, just as there are elementary carriers of electricity (the electron and proton), there may prove to be an elementary particle of magnetism. It would have a "magnetic charge", and as the charge could be either "north" or "south" the hypothetical particles were called **monopoles.**

The existence of a magnetic monopole would contribute to the symmetry which electromagnetic theory now lacks. From the viewpoint of present-day theoretical physics magnetism is a byproduct of electricity, appearing only as a result of the movement of electrically charged particles. Considerations of symmetry would suggest the existence of magnetic particles responsible for magnetic fields and whose motion would, furthermore, also generate electrical fields, just as moving electrical particles can generate magnetic fields. Like electrons, the magnetic particles would emit and absorb electromagnetic radiation (light, for instance). Furthermore, just as high-energy photons can create pairs of oppositely charged electrical particles, the electron and positron, such photons can also produce a pair of magnetic monopoles.

Dirac enunciated his magnetic monopole hypothesis at about the same time as he predicted the existence of the positron. The idea gave impetus to numerous investigations in both theoretical and experimental physics—alas, with no success. Experimenters were unable to detect any trace of monopoles. On the other side, no theoretician has been able to suggest convincingly why such particles could not exist. It might seem to some that all this is not enough to arouse interest in the hypothetical particle, but actually there is something in all this worth wondering about.

The thing is that it is more or less the rule of nature

that, if there is no law prohibiting an event or phenomenon, there is a good probability of it occurring. More succinctly this can be formulated as: whatever can be will be. Therefore, until such time as a law prohibiting the existence of monopoles is discovered physicists will be inclined to give them the benefit of the doubt. Besides, the discovery of a prohibiting law would be as great a scientific achievement as the discovery of the monopole itself.

The problem of asymmetry in electricity and magnetism has been worrying physicists for almost a century. It appeared after Maxwell brought magnetism and electricity together in his unified electromagnetic theory, one of the greatest accomplishments of 19th-century science. But the fact that both electrical and magnetic phenomena derive from the existence of only electric charges is hard to accept. Ever since, in 1862, Maxwell enunciated his beautiful equations of electromagnetism the absence of magnetic charge in them has seemed rather unnatural.

As a matter of fact, there actually is a place for magnetic monopoles in the set of Maxwell's equations. In one of them the right-hand portion is the density of electrical charge, in another it is the current of moving electrical charges; in the remaining two it is zero. To give the four equations the symmetry they lack, all one must do is replace one of the zeros with magnetic charge density and the other with the flux of moving magnetic charges. In other words, the zeros in the right-hand parts of the equations are as it were places "reserved" for monopoles. If monopoles exist no new equations are needed to describe them.

The need for monopoles becomes even more apparent when the Maxwell equations are written down in terms of relativity theory. Here we have only two equations: one containing a source of electric nature, the other with the right-hand part equal to zero—which could be replaced by a source of magnetic nature.

Dirac carried out some mathematical research which led to the interesting conclusion that, if the monopole exists, its magnetic charge must be quantized like the electrical charge. He even computed the monopole's magnetic charge quantum. Investigating the possible interaction of a monopole with an electrically charged particle, he came to the conclusion that the product of a monopole magnetic charge

multiplied by a particle electric charge should be numerically equal to a quantity determined by such universal constants as Planck's constant or the speed of light. In the "natural units" physicists frequently employ, the smallest value of this product (except zero) is one-half. As, in these units, the smallest value of the electric charge is unity divided by the square root of 137, the smallest magnetic charge that can be transferred by a monopole must be equal to one-half the square root of 137. In other words, the quantum of the monopole's magnetic charge is 68.5 times greater than the electrical charge quantum. Hence, two monopoles interact with a force $68.5 \times 68.5 = 4{,}692$ times greater than the force with which two electrically charged particles interact at the same distance.

This theoretical conclusion is of great importance as the only prediction of its kind in physics: up till now no one has ever succeeded in predicting the magnitude of an interaction between elementary particles. The monopole's magnetic charge theoretically computed by Dirac is the hypothetical particle's only characteristic obtained by direct calculation. However, even with this quantity alone a number of interesting conclusions can be drawn concerning the possible properties and behaviour of monopoles. Thus, we obtain that the monopole is heavier than all known elementary particles: at least three times the mass of the proton (provided, of course, that it exists at all). Another point to be made is that it is perhaps wrong to speak of the monopole in the singular as, again providing that it exists at all, we can expect there to be a variety of types of monopoles, just as there is a variety of electrically charged particles: some may be heavier than others, some may take part in nuclear interactions or possess spin, others may not, etc.

Assuming monopoles exist, how are they produced, how do they live and die? And where can they be found?

In investigating production and annihilation processes we should always remember that they must obey the law of conservation of magnetic charge. This means that a monopole, once produced, cannot vanish before it meets another monopole of opposite magnetic charge. (Monopoles can apparently be observed very rarely, hence encounters between them must be even rarer). On colliding a north and a south monopole would annihilate, but their total

magnetic charge before and after the collision would remain zero. It also follows from the conservation law that monopoles can appear only in north-south pairs. Again, the total magnetic charge remains zero, just as in the creation of an electron-positron pair the total electric charge is zero.

If monopoles exist it is natural to expect them to form in the manner of pairs of electrically charged particles, i.e., as a result of strong collisions between other particles. An example of such a collision could be the interaction of protons of very high energies sufficient to create the mass of two monopoles. Such energetic protons can be produced in modern accelerators. Another, more preferable, source of monopoles could be high-energy cosmic rays—both primary (mainly protons) and secondary (mainly photons produced in collisions of primary particles with atoms of air). Both often possess such high energies that they could be capable of producing monopole pairs in collisions with nuclear particles even if their mass is hundreds of times greater than that of the proton.

Besides, monopoles could also reach the earth from surrounding space. They may in fact even be present as an extremely rare component of cosmic rays or be found in meteorites. Both these possibilities were investigated not long ago by Goto in Japan.

To begin with, he noted that monopoles reaching the earth with cosmic rays should possess fantastic energies. Thanks to their big charge they could be accelerated remarkably effectively in a magnetic field, much more effectively than, say, protons. In the cosmic vacuum and over the vast distances of outer space even the weak magnetic fields of interstellar space would accelerate monopoles to average energies of 100,000 million electron volts. Such energetic monopoles would pass right through the atmosphere and deep into the earth.

For the same reasons monopoles, if we could only produce them, would be ideal particles for laboratory accelerators. It has been computed that a magnetic field of 10,000 gauss (something easily obtainable in modern laboratories) could boost a monopole's energy by 200 MeV per every centimetre it travelled. A monopole accelerator only two metres long could surpass the most powerful of existing accelerators, which are up to a kilometre in circumference.

In addition, very few monopoles would be needed for experiments as they could be retrieved from the targets and used over and over again. Thus, a monopole accelerator could, in principle, operate indefinitely by using and re-using the initial quantity of accelerated particles.

As for monopoles in meteorites, Goto noted they could well be produced in them by cosmic rays. Monopole pairs could scatter in the reaction and, separated in an iron meteorite by one-thousandth of a centimetre, they would no longer be able to annihilate. Thus, monopoles once created in, or captured by, a meteorite would remain in it forever, held by forces analogous to those that hold electrons in metal. And owing to the high value of the magnetic charge the monopoles' binding energy in iron would be hundreds of times greater than the binding energy of electrons.

Today it is considered that iron and rock meteorites have been moving in the solar system for hundreds of millions of years. Continued bombardment by cosmic rays over so long a period could well produce monopoles in many of them. Some of the meteorites currently on view in museums or scattered over the surface of the earth may perhaps contain magnetic particles waiting to be discovered.

Goto also indicated one more place where monopoles could be found. Suppose cosmic rays produce a monopole pair in the upper atmosphere. On its way through the atmosphere the particles' motion is retarded. The northern monopole will be deflected by the earth's weak (less than one gauss) magnetic field to the north, the southern monopole, to the south. Ultimately each monopole travelling along the lines of force of the earth's field will reach the surface, moving at relatively low speed. If, on arriving, the monopole hits a chunk of iron ore it will be captured by a sizeable magnetic field. Therefore, iron ore at the surface of the earth could be searched for monopoles.

But if monopoles exist, how can they be extracted from the materials in which they are embedded? There are two possible ways: one is to apply a powerful magnetic field, the other is to destroy the magnetism of the material holding the monopoles (a meteorite, for example) by heating or chemical treatment. It has been calculated that the extraction of a monopole from pure iron would require a magnetic field of around 60,000 gauss, which can be produced with the help of special magnets. A correspondingly wea-

ker field would be needed to extract monopoles from iron ore or other less magnetically active materials.

It would not be difficult to detect and identify a monopole. Owing to the rapid dissipation of energy in passing through matter a monopole should leave such a thick track in nuclear photoemulsion that it couldn't possibly be confused with any other particle. It would behave differently than electrically charged particles in a bubble or cloud chamber in a magnetic field.

According to one theory, in passing through air a monopole could gather a "cluster" of oxygen molecules, forming a weakly associated "magnetic molecule". Such a formation would be then entrained by the earth's magnetic field until it reached the surface. If it landed on a piece of iron the monopole would be extracted from the oxygen cluster and captured by the powerful forces that hold it in iron.

The possibility cannot be excluded that monopoles can penetrate into atoms and interact with nuclei. If that is so they are bound so strongly with the nuclei that it would be as hard to remove them as to force a child to relinquish a favourite toy.

In 1962 two attempts were made, at Brookhaven and Geneva, to detect monopoles with the help of 30 BeV accelerators.

At Brookhaven the target was a thin aluminium lamina and it was bombarded with high-energy protons. The bombardment products included a variety of scattering particles, among them pi mesons and antiparticles, and it was hoped that monopoles might appear among the fragments. A trap for monopoles was set up in the shape of a tank containing a 25 centimetre layer of engine oil which, it was calculated, was sufficient to trap any monopole produced in the proton beam. An electromagnet (solenoid) was used to extract any monopoles that might be trapped in the liquid. Two types of detectors were used in the experiment. One was a scintillation detector: a tube filled with liquid xenon, which scintillates when particles pass through it. Monopoles were expected to produce a brighter scintillation than electrically charged particles. The other detector, used in a different series of tests, was a nuclear photographic emulsion in which monopoles were expected to leave thicker than normal tracks.

In the Brookhaven experiment a total of 6,000 million

million high-energy protons hit the target. Not a monopole was discovered. (The protons were not wasted, of course, as simultaneous experiments with other particles produced by bombarding the target were carried out.) Similar experiments with the CERN accelerator also failed to yield a single monopole track. The energies used in the experiments were sufficient to create monopoles of triple proton mass. Thus, the least can be said as a result of the experiments that if monopoles exist at all they must be more massive than that.

More recently Goto, Kolm and Ford carried out a search for monopoles among cosmic ray products. They used meteorites and iron ore subjected to cosmic rays. In the experiments with iron ore a small but very powerful magnet capable of generating pulses of magnetic field intensity of up to 60,000 gauss was used. This should have been sufficient to extract any monopole trapped on the surface of the ore. The equipment provided for the acceleration of extracted monopoles to energies of more than 1,000 MeV. No monopoles were found in iron ore. Nor were any found in meteorites, which included samples from the Harvard museum which were subjected to a field intensity of 100,000 gauss.

The absence of magnetic particles remains a physical paradox which will worry physicists until they can find a satisfactory explanation for it.

CREATIVE VACUUM

Now, armed with new concepts concerning the nature of vacuum, we are in a better position to appreciate the attempt of Bondi and Gold to save the expanding universe from the dilution of matter. The Bondi-Gold model is rid of the paradoxes associated with expansion, infinity and eternity. However, in the words of Soviet cosmologist G. I. Naan, the price is exorbitant and it is a case of "Satan being purged by Beelzebub". The basic idea of Bondi and Gold is not new and we have heard of it before: the spontaneous creation of matter out of nothing.

Like Hoyle and Jordan, Bondi and Gold have arbitrarily ascribed space one single property: once in every thousand million years every metre of space produces a single atom of hydrogen. The requirement is certainly a modest one. At this rate in all the eons since the creation a volume of space equal to the earth in size would have yielded one ten-

millionth of a gram of hydrogen. But this is no justification, and there is no escaping the fact of creation. Bondi leaves no doubt as to this when he states that it should be clearly realized that the stated creation is the creation of matter, not from radiation but from nothing.

Bondi and Gold's hypothesis gained in attraction when Hoyle and MacCray rid it of "Beelzebub" with his trampling under of the most basic law of the universe, the principle of the non-creation of matter.

Hoyle and MacCray postulated that the matter making up for the dilution of the expanding universe is produced out of a material "creative field". It pervades the universe, it is everywhere, but it is very weak, which is why it hasn't yet been discovered.

We know a variety of fields: gravitational, electromagnetic, electron-positron, meson, neutrino—so there is nothing objectionable in the idea itself. But the creative field also has to derive energy from somewhere to create particles. If it exists it should manifest itself in some effects associated with the red shift in the spectra of fleeing galaxies. It is to be expected that in the near future the Hoyle-MacCray theory can be verified experimentally. At the same time we can already say that it does not contradict our notions of the nature of vacuum, our concepts of the nature of four-dimensional space-time.

Let us try and sum up in the most general terms what we have learned so far. We know that to every quantized field corresponds a specific type of field particles, and that to every type of particle corresponds a quantized field of force. There are no real particles in vacuum, only virtual oscillator particles performing zero oscillations. The existence of oscillators is an intrinsic and objective property of space; the number of oscillators of different types is equal to the number of different particles. Therefore potentially the reserve stocks of particles preventing the expanding universe from diluting are there. True, they are virtual particles, but it is clear that we are on the right road.

The photon and pion, which are their own antiparticles, can be regarded as a special case of particles that have antiparticles. Therefore, as a rule, the emission process is accompanied by the creation of a particle-antiparticle pair. Real space—physical vacuum—stands before us as a to-

tality of all physical fields and an inexhaustible reservoir of all particles and antiparticles without exception.

To this should be added that the virtual particles filling space may become real if they are imparted a sufficient store of energy. The explanation is that, according to Dirac's theory, the proper energy of these particles is, as we know, less than zero. They are particles with negative energy.

Antiparticles are holes in vacuum. The discovery of an antiproton or antineutron entails the "knocking out" of a hole with powerful energy blows.

When we spoke of the creation of antiparticles from a more formal standpoint, without due analysis of Dirac's conceptions of vacuum, this was done merely for the sake of convenience. This is just what physicists do when they refrain from speaking of the structure of vacuum solely for the sake of simplifying the mathematical computations.

These were the ideas which enabled physics to get rid of action at a distance and explain interactions, not in terms of properties of bodies, but as properties of physical vacuum and field, that is, properties of space itself.

But here again a certain dualism appears. We explain gravity in terms of geometrical properties of space, and electromagnetic and all other fields in terms of quantized, purely physical properties. Some theoreticians are, naturally, looking for ways (we shall speak of them later on) to overcome this dualism. This can be achieved along one of two roads either by discovering the gravitational field quantum, of which we just spoke, or by developing geometries for all fields. So far neither road has led to success.

There is, however, nothing terrible in having gravitation associated with space geometry, and all other fields with the quantum properties of physical vacuum. The thing is to learn to reckon with phenomena which simultaneously involve spatial geometry and physics. An example of such phenomena is the evolution of stars.

Back in the thirties Lev Landau and the Indian physicist S. Chandrasekhar showed that a celestial body with no internal energy sources and with a mass exceeding a certain threshold must contract indefinitely. But how does such contraction end? For indefinite contraction must, in the first place, lead to an increase in gravity and nuclear forces that defies the imagination. Besides, we have no way of being

sure that in such circumstances physical vacuum will remain absolutely stable. At high energy densities virtual particles may become quite real. And if a sufficient number of them appears the gain in gravitational and nuclear energy may exceed the energy expended in the "creation" of particles. What happens then?

At this point we will have to invade the domain of fantasy. Therefore let us first investigate a few things about the evolution of stars. And if, in speaking of neutrons or hyperons, we had in mind individual particles, now we will have to get acquainted with new properties that appear when countless populations of particles get together in neutron or hyperon stars.

PART FIVE

The Megaworld

THE STARS LOOK DOWN

Night after night, century after century the countless stars traverse the skies. Men are born and die, civilizations rise and fall to give place to others, but every night the same stars rise over the horizon.

In the stars the universe shows itself to be both ordered and inexhaustible. There would appear to be no end to the diversity of remote luminaries, but man has managed to reach out to the limits of possibility beyond which even nature does not venture.

There are stars thousands of times bigger than the sun. Epsilon B Aurigae has a diameter 2,700 times the sun's, but in mass this largest known star is only 25 times greater, and its mean density is thousands of millions of times less than that of the terrestrial atmosphere. The giant cannot be seen even in the most powerful telescope as it is basically an infrared star that emits rays invisible to the eye. There are stars of only one-third the earth's diameter and comparable more with the moon in size. But the moon is a cold, lifeless world while the star listed under number 457 in Wolf's catalogue, for example, is a gaseous sphere millions of times denser than steel and twice as hot as the sun. There are stars whose luminosity is hundreds of thousands of times the sun's, such as Zeta Scorpii, visible to the eye as a not so bright star of third stellar magnitude, while the star Lalande 212558B, if it occupied the place of our sun, would give off only 0.000031 of its light.

There are double, or binary star systems. In the constellation Cepheus, for example, there is a binary denoted VV one member of which is a cool giant, the other is similar to the sun. In the constellation Eridanus there is a triple star, in the Lyra there is a system of four stars, and slightly to the left and above Orion there is a system of six.

Our solar system is a member of a gigantic conglomeration of different types of stars, star clusters and associations, gas and dust nebulae. These diverse and apparently randomly scattered elements are all dynamically linked in a single system, the Galaxy or Milky Way. It contains some 10^{11} stars and its total mass is estimated at 2.6×10^{44} g, which is 10^{11} times the mass of the sun. Gaseous matter accounts for 2 per cent of the total, and interstellar dust for even less.

The Galaxy is a huge spiral structure with the brightest stars concentrated predominately in a flattened "disk" from which the spiral arms extend. The bulk of the Galaxy's mass is contained in an ellipsoid bulge called the nucleus. The Milky Way is approximately 30,000 parsecs in diameter and a ray of light requires 100,000 years to span it from end to end. Like a gigantic cartwheel the Galaxy revolves around an axis passing through the nucleus.

The stars are a good example of nature's ability to achieve diversity in unity, order in diversity. The sun is an undistinguished star, one of millions others like it. Yet it is in its way unique, and the same can be said of any other star. There are no two stars with completely identical spectra. Nevertheless, in the first approximation stellar spectra fall into a sequence of classes denoted by the letters O, B, A, F, G, K, M. Each class is subdivided into ten subclasses, e.g., F5, G8.

Differences in stellar spectra are in the first place due to the temperature at the surface. The hottest stars of spectral class O have a temperature of 40,000 degrees, the coldest class M stars are around 1,000 degrees. The sun, whose surface temperature is 6,000°, belongs to class G. A star's colour is directly related to its temperature: the hottest are blue, followed by white, yellow, red.

The luminosity of some stars fluctuates. Such stars are known as variables and they can be subdivided into two main classes, pulsating and eruptive.

As their name implies, pulsating stars regularly contract and expand. Physical conditions inside a star change accordingly. When it contracts it grows hotter and its brightness increases. Expansion causes the temperature to drop and the luminosity to decrease correspondingly. Some pulsating stars have a regular period (regular variables), in some the regularity is less pronounced (semiregular

variables), in some the pulsation is apparently quite random (irregular variables). All pulsating stars belong to the classes of white, yellow or red giants; the pulsation periods of white and yellow stars are more regular and shorter than of red stars.

White and yellow giants and stars with luminosities from 100 to 4,000 in terms of the sun (supergiants) and pulsation periods ranging from 86 minutes to 60 days are called cepheids. Cepheids with periods of less than 24 hours are known as RR Lyrae.

An interesting type of irregular variable is the low-luminosity Tau Tauri, which alternately displays rapid and slow variations of light. There are also others with alternating periods of fast and slow luminosity fluctuations. There are also variables which brighten suddenly to tens of times their original luminosity and then rapidly revert to the normal state.

It is not our purpose to describe stars of different classes in detail. However, in considering the properties of space, the fates of galaxies and transformations of matter we must also speak of them. In stars scientists seek answers to such "eternal" questions of man as: What is the universe? Was there a beginning of the world? Is the universe finite or infinite in time?

The unaided eyes of our ancient forebears could make out five or six thousand stars. Today the number of stars is listed at 10^{20}.

The American astronomer Harlow Shapely offered the following interesting ratio:

$$\frac{\text{star}}{\text{man}} = \frac{\text{man}}{\text{atom}}$$

Which is to say that man is bigger than a hydrogen atom in approximately the same ratio as the sun is bigger than man. Man is thus as it were the geometrical mean between stars and atoms, with infinities on both sides. We can learn nothing of the evolution of stars without assaulting the atomic nucleus. We can gain no clear idea of the role of elementary particles in the universe without knowledge of the evolution of stars. That is why we interrupted our story of the geometry and physics of space to say a few words about the evolution of stars.

A hundred years or so ago the eminent German astronomer and mathematician Friedrich Bessel turned his telescope to the brightest star of the heavens, Sirius. What was his amazement when he found that in its course across the sky Sirius seemed to wobble from the straight path characteristic of all other stars. The explanation to this anomaly is simple enough: Sirius has an invisible companion which affects its motion. As we know, binary systems are fairly common in the universe. In fact, G. Kuiper estimates that no less than 80 per cent of the stars in the Galaxy belong to groups of two, three or more.

The assumption that Sirius had a companion was confirmed when astronomers discovered in the expected place a very dim star only hundredth fractions of the sun's luminosity. Its mass was calculated from the perturbation it caused in the motion of Sirius. And here astronomers were amazed to find that the mass of Sirius B, as it was called, is about that of the sun.

Why such different luminosity in stars of similar mass? There were two explanations: Sirius B is either very small or very cool. The latter was the simpler explanation, and Sirius B was listed as a cool star. Astronomers lost interest in it: it was nothing more than an ordinary cool star.

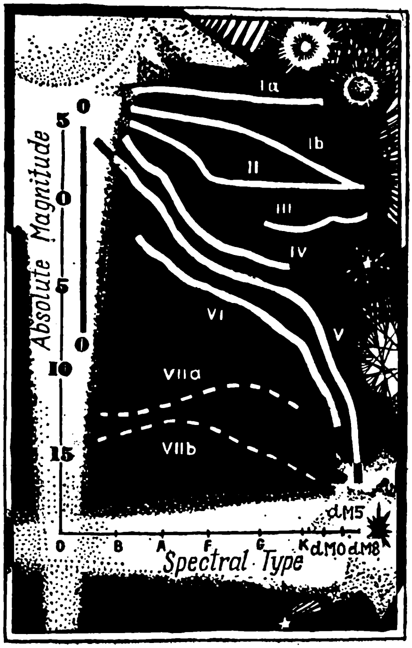
Years passed. Astronomers learned to analyse stellar spectra. From the colour they could judge of the temperature at the surface, just as a smith judges the temperature of iron as it changes its colour from cherry-red to blue-white.

To the astronomers' amazement, Sirius B proved to be a very hot star, in the white class with a temperature of around 8,000 degrees at the surface. Thus its low luminosity had to be explained by its small size. Investigations revealed that the star's diameter is 40,000 km, i.e., only about three times the earth's. But the density of Sirius B is 60 kg per cubic centimetre, 1,000 times the earth's! Man has never seen anything even remotely like it. The heaviest substance on earth weighs no more than 23 grams per cubic centimetre.

The conclusion concerning the tremendous density of Sirius B is not merely speculative. It derives from the already familiar "red shift". Only in this case the shift is

due not to the distance of the object but to gravitational effects. In overcoming the star's huge gravity pull photons dissipate a portion of their energy, as a consequence of which the frequency of light oscillations decreases.

Stars of the type of Sirius B, with anomalously low luminosities due to small size and tremendous density, have been given a name which aptly describes their essence:



white dwarfs. Today more than 60 such stars are known, and there are probably many more in the Galaxy. True, not all the white dwarfs are really white. There are cooler "yellow" white dwarfs, "red" white dwarfs and, perhaps, even "black" white dwarfs invisible in optical telescopes.

What forces are capable of compressing matter to such density and what is its state? Before answering this question let us get acquainted with the classification of stars as a whole and the place white dwarfs occupy in it.

There are certain relationships between the fundamental characteristics of stars. In 1905, the Dutch astrophysicist Ejnar Hertzsprung showed that red stars could be classified

into two groups of high and low luminosity. In 1913, Henry Russel compared star luminosities with spectral classes. He charted his findings on a diagram, which was expanded and verified as new data accumulated. The Hertzsprung-Russel diagram, as it is called, assigns to every star a point one coordinate of which is the temperature (spectral type) and the other is the luminosity (absolute magnitude).

Most stars on the diagram form long narrow strips called sequences.

The most abundant in stars is a strip running diagonally across the diagram and called the **main sequence** (V in the figure on p. 301). In the upper left-hand part of the diagram are hot blue giants; they are followed by white, yellow (including the sun) and, finally, faint red stars, relatively small in size and mass, at the lower right of the sequence.

The brightest stars of the main sequence are 10,000 times more luminous than the sun, the weakest dwarfs are hundreds of thousands of times dimmer. The surface temperature of some blue stars is as high as 50,000 degrees, that of red dwarfs may be less than 3,000 degrees. Along the main sequence masses of stars decrease from 40 to 1.1 times the sun's, and radii from 20 to 0.1 the sun's.

To the right and above the main sequence lie the supergiant (Ia, Ib) and the yellow giant (II, III) sequences. The luminosity of these stars is tremendous and they are thousands of times bigger than the sun, but in mass they exceed the sun only a few times and their density is accordingly very small.

Thus, Antares, with a radius 280 times the sun's, exceeds it only 30 times in mass and has a mean density of 0.0000016 g/cm^3—a thousand times less than the earth's atmosphere at sea level!

Just above the main sequence lies a sequence (IV) of stars with temperatures not greatly different from the main sequence. These are subgiants, several times bigger and not so dense as main-sequence stars.

Subdwarfs, discovered by the American Gerald Kuiper and the Soviet astronomer P. P. Parenago, form group VI, lying below the main sequence. In mass and radius they approach the red dwarfs but exceed them in luminosity.

The lower left-hand portion of the H-R diagram (VIIa, VIIb) is occupied by stars with temperatures high enough to

classify them as "white" and which are small enough to be rated "dwarfs". White dwarfs are fairly common and they form a distinct stellar class.

Finally, to the left of the stars of spectral class O is a sequence of very hot blue-white stars discovered in 1947 by B. A. Vorontsov-Velyaminov (the vertical line O-O).

Besides the spectrum-luminosity diagram, astronomers also use a mass-luminosity diagram. The luminosity of stars generally increases with mass, a relationship especially apparent on the main sequence. But it breaks down with respect to white dwarfs, subdwarfs and certain other types of stars. Evidently some secret of nature lies behind this.

A legitimate question in examining the H-R diagram is: Why are there spaces between stellar classes? Why isn't the diagram filled evenly? After all, one could expect a gradual change of properties from class to class. As of today, however, we can do no more than record the fact that, if there are stars between the sequences they are unstable, undergoing a relatively swift change of properties that takes them into the nearest classes.

EXPLODING STARS

The most spectacular manifestations of stellar instability are explosions of so-called **novae** and **supernovae.** They are also of special interest to astrophysicists and cosmologists.

"On the day of Chi-Chu in the fifth moon of the first year of the period Chi-Ho, a new guest star appeared southeast of the star Tien-Kuan.... It could be seen in the daytime, light radiated from it in all directions, and it was reddish-white. It was observed for twenty-three days."

This is an excerpt of a Chinese Chronicle written in 1054, when two unknown astronomers, a Chinese and a Japanese, recorded one of nature's rare phenomena, the explosion of a supernova, in their diaries.

When a faint star suddenly flares up and then quickly dims again, throwing off an envelope into outer space, astronomers call it **a nova**. Nova's outbursts may be recurrent.

A supernova is a much more awesome event, an exploding star, which is what the 11th-century Chinese astronomers observed. They stated the star's position with great ac-

curacy. Today, more than nine hundred years later, a small star of ninth magnitude in the constellation Taurus can be seen there in a telescope. What makes this star of special interest is that it is situated at the very centre of the Crab nebula, which is expanding in all directions away from it. The rate of expansion is so great that changes in the nebula's size are seen on photographs made 20 or 30 years apart—and this at a distance of 5,000 light-years! It has been calculated that the nebula is expanding outward from the star at a speed of around 1,000 km/sec. These are two stages of the same phenomenon—the explosion of a supernova—separated by nine centuries. The star sheds a large part of its mass, which thins out into space, forming the nebula we can see today.

Why do stars explode? What causes such an instantaneous loss of stability? All we can assume is that we have here a stupendous nuclear blast in which a colossal amount of energy is released. The star's magnetic field may possibly have something to do with it. (Some stars have been observed to have variable magnetic fields, though no fluctuation law of the field has been discovered.) But the questions posed above still remain largely unanswered.

Now we can return to the question asked before: What are the forces that compress matter to the density of a white dwarf?

First of all, gravity. At the surface of Sirius B the gravitational force is 30,000 times greater than on earth. A man there would weigh 1,800 tons.

At such tremendous densities the average distance between atomic nuclei becomes smaller than the radius of the atom and electron shells would have had to interpenetrate. As this is impossible the electrons are stripped from the nuclei. When the density becomes so great that distances between nuclei become equal to or less than the radius of the smallest electron orbit all the electrons are stripped away and matter acquires the state of an electron-nuclear gas. At this density one cubic centimetre contains about 10^{28} electrons, the degeneracy temperature for the electron gas being 10 million degrees. As the temperature even in the interior of a white dwarf is much higher, the electron Fermi-gas is in a state of complete degeneracy.

The density of matter inside a star decreases from the centre to the surface. As temperature and degree of degene-

racy of the electron gas decrease with density, at the surface atoms are not ionized at all and are in their normal state. In Sirius B it is estimated, for example, that the electrons are in a state of degeneracy for about 77 per cent of the total matter. Such are the conclusions of the theory of white dwarfs elaborated, as mentioned before, by Lev Landau and S. Chandrasekhar.

NEUTRON STARS

No astronomer can claim to have observed a neutron star. For one, they must be very small and very faint. However, the inevitable transition from white-dwarf to neutron-star state predicted by theory (L. Landau, R. Oppenheimer, M. Volkov) gives hope that they will eventually be discovered. This will be facilitated by the development of new branches and principles of astronomy—neutron astronomy and gamma astronomy, to name but two—and by observations with astronomical instruments carried above the terrestrial atmosphere.

How does the evolution to neutron stars occur? In speaking of white dwarfs we mentioned their high density—up to 10^8 g per cubic centimetre. How will matter behave at higher densities still?

V. A. Ambartsumyan allows for the existence of virtually unlimited densities characterizing a special, prestellar state of matter. The possibility of such great densities developing may also be inherent in the nature of white dwarfs. A dwarf may be compressed further by gravitational forces if its internal pressure, which is due mainly to the electron gas, can no longer balance the gravitational force.

At a density of matter of 10^8 g/cm^3 and more electron density exceeds 10^{32} per cubic centimetre; the limiting energy of the degenerated electron gas becomes so great that most of the electrons begin to move at speeds approaching that of light.

At such density and energy levels the state of the electron and nuclear gases becomes energetically unprofitable. For the star's total energy to decrease a nuclear reaction involving electron capture must take place, and a large portion of the protons in the nuclei turn into neutrons:

$$p + e^- \longrightarrow n + \bar{\nu}_e$$

But, as is known, a nucleus is stable only if the proportion of protons and neutrons in it is right. If there are too many neutrons it disintegrates into nucleons. In white dwarfs at densities up to 10^8 g/cm^3 atoms degenerate into an electron gas; in neutron stars, where the density is much higher, the nuclei themselves disintegrate, and the star comprises three gases: neutron, proton and electron. Just as in white dwarfs, there is the same number of protons and electrons, and the star is electrically neutral. The number of neutrons increases with the density, while the number of protons and electrons decreases. By the time there are 10^{34} neutrons per cubic centimetre they exceed the number of protons and electrons a thousand to one.

Back in 1938, Oppenheimer and Volkov showed that a neutron star would be in equilibrium if its mass lies within 0.3 to 0.7 of the sun's. The radius of such a star should be 6 to 20 kilometres! It is hardly surprising that neutron stars have not been observed. The gravitational fields of neutron stars are as great as the stars themselves are small, and the gravity pull at the surface is 200,000 million times greater than at the surface of the earth. This force is balanced, not by the pressure of the degenerated electron gas as in white dwarfs, but by the pressure of the neutron gas.

As in the case of white dwarfs, the outer shell of neutron stars consists of electrons and bare nuclei and, at the very surface, non-ionized atoms. The mass and thickness of this layer is, however, negligible.

For a white dwarf to be compressed to the size of a neutron star a fantastic work must be done which, as it is transformed into energy, would have heated the star tremendously, making it unstable. But the gravitational force compresses the star very gradually, and the energy is released little by little. If the energy were emitted only as radiation the compression would take many thousands of millions of years, longer than the lifetime of the Galaxy, and neutron stars would simply have had no time to be formed. The contradiction is resolved with the help of the ubiquitous neutrino. Neutrino streams pass easily through the star, carrying off most of the energy.

It is interesting to note that neutron stars must display such a typical "subatomic" property as mass defect. What remarkable unity! The energy dissipated in the contraction is so great that it appreciably affects the mass of the

star. Like an atomic nucleus, the mass of a neutron star is less than the sum of the masses of all the atoms which went into its making. The mass defect is the greater the higher the star's density. Actually, a neutron star can be regarded as a gigantic atomic nucleus made up almost wholly of neutrons.

Neutron stars have another interesting property, pointed out by Davydov and Zwicky. As is known from general relativity, a light ray is bended by a gravitational field. Near the sun the deflection amounts to fractions of a second of angle, thanks to which the stars seem slightly wider apart.

A neutron star curves space-time considerably, the deflection of light is so great that the gravitational field acts like an optical lens gathering light from many stars in a bunch. Perhaps this property will in time help discover the first neutron stars.

Is there any limit to the density of a star? Are neutron stars the end, or can they undergo further compression? In an attempt to answer these questions V. A. Ambartsumyan and G. S. Saakyan developed their theory of hyperon stars.

A further increase in density leads to the formation of hyperons. When the density exceeds 10^{15} g/cm^3, which is three times greater than the density of an atomic nucleus, the neutron gas limiting energy exceeds the hyperon rest energy. Therefore transmutation of a portion of the neutrons into hyperons, which reduces the total energy of the system, is thermodynamically advantageous.

In these circumstances the hyperon is more stable than the neutron. This derives from the Pauli principle. Hyperon decay yields nucleons of smaller energy than the limiting energy of degenerated nucleon gas already present in the system. In the gas, all the lower energy levels are tightly filled and the Pauli principle prohibits the appearance of new particles, which is why hyperons do not decay. Other elementary particles in a hyperon star include small amounts of negative muons and pions whose stability is ensured by the highly degenerated electron gas.

Soon after the first hyperons appear their concentration matches that of neutrons, but, like in a neutron star, electrons are a thousand times less abundant.

In equilibrium, a hyperon star of the same mass as the sun is only a few kilometres in diameter. Most of the mass

is concentrated in a superdense core consisting of hyperons, nucleons, pions and a sprinkling of muons and electrons. The hyperon core is surrounded by a layer consisting mostly of neutrons; above it lies an envelope of bare nuclei and electrons, followed at the very surface by a shell of atoms, the same as in neutron stars and white dwarfs. The mass of the outer shell, which is estimated to be only a few metres thick, is negligible.

All this applies to stable hyperon stars in equilibrium. The tremendous internal pressure caused by the particle gas is at every point balanced by gravitational forces. When the star's mass exceeds the equilibrium value the star explodes with the release of a tremendous amount of energy, some 20 per cent of the rest energy turning into electromagnetic and thermal radiation. This truly cosmic explosion must be like the explosion of a supernova.

When hyperons begin to breed in a star the mean distances between the centres of nucleons become equal to, or even less than, their size. It is hard to imagine the state of matter at such density. We cannot even predict what happens to the elementary particles in these conditions, whether they retain their identity or become something entirely different. Some physicists consider that at such small distances such concepts as elementary particle, space, and even time, lose meaning and new statistical laws describing unknown states of matter come into effect.

Perhaps this is what matter was like thousands of millions of years ago in the highly compressed universe in which the nuclei of elements and nuclear particles themselves were only just being created.

A degree of fantasy is always necessary in discussing such questions since our knowledge of the structure of elementary particles is still very conjectural. Small wonder that physicists are striving so stubbornly to increase accelerator energies so as to be able to see for themselves how elementary particles behave when they are brought very close together.

One is, of course, fully justified in expecting that, just as atoms break down and plasma appears when matter goes into the white-dwarf state, a deeper transformation of matter must take place in the transition from white dwarf to neutron star. The trouble is that today we are incapable of predicting or even imagining the nature of this trans-

formation. That is why the hyperon star theory rests on the assumption that particles retain their identities at supernuclear densities.

When nuclear scientists wrest this mystery from the microworld with the help of superpowerful accelerators, astrophysicists will be able to elaborate their superdense star theories and cosmologists will gain a clearer idea of prestellar matter.

WITNESSES OF COSMIC CATASTROPHES

Reinforced with some information about the evolution of stars, we can now go back to the unfinished story of cosmic rays.

Not so long ago many researchers held that the origins of cosmic rays lie mainly within the confines of our own Galaxy. This is at least true of particles with energies not exceeding 10^{17} electronvolts. Where do the galactic wanderers originate? For cosmic radiation to be sustained at a constant level particles with a total energy of 10^{39}-10^{40} erg/sec must be emitted somewhere. A common star like the sun expends 10^{21}-10^{22} erg/sec on cosmic ray emission. Assuming that all the stars in the Milky Way emit as much, the total energy is one million to ten million times less than the required energy. Does this mean that the assumption that cosmic rays originate in our Galaxy is wrong?

Besides stationary stars, the Milky Way has about 1,000 million magnetic stars, each emitting a million times more energy than the sun. True, even this accounts for only 0.1 to 1 per cent of the required energy. But there are other reserves. Novae and supernovae, V. L. Ginzburg and I. S. Shklovsky point out, are the principal sources of cosmic radiation.

A supernova explodes in the Milky Way on average once every 40 or 50 years. Only a few flares can be observed from the earth, however, as most of them are obscured by opaque interstellar matter lying in the plane of the Galactic disk.

Supernovae explode in other galaxies too. The light emitted in the explosion sometimes exceeds the combined luminosity of all the thousands of millions of stars in the galaxy, which is why supernovae can be observed from the earth.

A supernova explosion is a stupendous event. For example, the total energy emitted by the Cassiopeia A nebula 10,000 light-years away is 10^{51}-10^{52} ergs. This is 100,000 million times the annual radiation of the sun. Scientists estimate that at least one-tenth of all this energy went into the creation of cosmic rays. This alone is sufficient to make good the energy dissipation of the Galaxy's cosmic radiation over a span of 3,000 to 30,000 years. To be sure, most supernovae have a smaller energy yield, but even one per cent of the amount would suffice to sustain a cosmic ray level of around 10^{56}-10^{57} ergs for the Galaxy as a whole. Significantly, radioastronomers have obtained similar values for different galaxies.

However, there are exceptions.

In recent years astronomers have discovered new celestial bodies which radiate radio waves much like visible stars radiate light. Many of these radio sources have been identified with visible objects (like the Crab nebula and other remnants of exploded stars). On the other hand, two very strong radio sources are located in positions where optical instruments have not established the existence of visible bodies. A feature of major interests to astronomers all over the world is a galaxy called Cygnus A located 700 million light-years from us. It is the strongest known radio source.

Many attempts were made to photograph Cygnus A with the help of optical telescopes before the excellent telescope installed on Mt. Palomar in the United States yielded the remarkable picture of two apparently interpenetrating galaxies. Their central regions were distorted, deformed by stupendous gravitational forces.

A collision of galaxies, if that is what has been observed, should not, of course, be taken to mean collisions of individual stars, which lie hundreds of light-years apart. The stars themselves remain unchanged, only their paths are distorted substantially. The intermingling of the galaxies' gas and dust clouds changes their shape and yields temperatures ranging up to 100 million degrees.

The interstellar dust and gas of mutually interpenetrating galaxies begin to glow, magnetic fields change or break down, electrical phenomena take place the signals of which reach terrestrial radiotelescopes hundreds of millions of years after the event.

The total extension of the colliding stellar systems is a million light-years. By comparison, the distance between their respective centres is almost negligible: only 3,000 light-years. But how is such intense radio emission generated? An analysis of its strength and energy spectrum indicates that the emission cannot be due to heating of the colliding gases. Two foci of radio emission 120,000 light-years apart were found: this is almost three times the visible extension of the galaxy. Perhaps these radio sources are located in the scattered clouds of colliding gases? But whence the tremendous energy of the radiation, which is tens of times the light energy of the colliding galaxies? The rarefied outer regions of the galaxies could not produce it. This gave rise to the hypothesis that the event in Cygnus is a collision of a galaxy with an antigalaxy or its immersion in a cloud of antimatter. This would easily explain the huge energy output. The hypothesis, however, appears fantastic and lacking in substantiation.

Some researchers consider that the object Cygnus A is two galaxies in separation, not collision. Only the future will shed light on the mystery.

The tremendous energy of the cosmic rays from Cygnus A, which is 100,000 times greater than the energy output of normal galaxies, is one of the exceptions mentioned above. In amount of radio radiation reaching the earth Cygnus A is inferior only to the sun and Cassiopeia.

The nebula Centaurus A, located closer to the earth, presents a picture similar to that of Cygnus A, except that the radio sources are up to 650,000 light-years apart. Evidently Cygnus A and Centaurus A are objects of the same type but at different stages of development. In some galaxies explosion-like events take place in which streams of gas and cosmic radiation are ejected. But whereas the explosion of a supernova can in some way be explained in terms of different kinds of nuclear processes, the forces and causes responsible for exploding galaxies remain a mystery.

One suggestion is that we are witnessing (relatively, of course, for the events took place hundreds of millions of years ago) turbulent processes of star formation.

Still, however intense the extragalactic sources of cosmic rays they do not play an important part in the radiation balance of the Milky Way. Or so scientists thought

until recently. Cosmic showers of extragalactic origin are extremely rare and have been observed only twice.

A shower of record intensity was registered at a cosmic ray research centre in New Mexico, USA, during which from 20 to 40 thousand million charged particles formed in the atmosphere. The ionization could only have been caused by particles entering the atmosphere at energies of 10^{19}-10^{20} eV. As we shall see later on, it follows from the theory of the origin of cosmic rays that acceleration of particles within the Milky Way cannot impart them energies of over 10^{19} eV. A particle with a higher energy must be of extragalactic origin. In only two cases have showers been recorded of such intensity that they can be explained only in terms of particles coming in from beyond the Galaxy. The first was observed by the same centre in December 1959.

The most valid hypothesis to date is that the dissipation of energy of cosmic rays in the Galaxy is compensated by "injections" from supernovae. From the energy aspect everything is all right. But the velocities.... The thing is that the speed of gases in the spreading shell of a supernova does not exceed one thousand kilometres per second. This is many times less than the relativistic velocities of cosmic rays. The idea necessarily suggests itself that perhaps there exists some natural accelerator capable of boosting cosmic particles to the required velocities.

GAS ACCELERATORS OF THE COSMOS

For many years astronomers had thought of gas nebulae as of huge clouds of extremely rarefied gases with no structural features reflecting light from nearby stars. G. A. Shain and V. F. Gaaze, analysing photographs of various nebulae, found that they have a fibrous structure. Some have filaments encircling clouds of gas, in others most of the gas is in the filaments (which suggested the name Hammock for one of them). Spectral investigations show that nebulae are in constant motion and change. Some appear to be falling apart, others are elongated, as though drawn out by unknown forces.

Shain arrived at the conclusion that the motions of nebulae are in many ways dependent on the action of interstellar magnetic fields. What is the source of magnetism in the universe?

First of all, there is stellar radiation. The shortwave radiation of stars batters the atoms of interstellar gas, churning them up into chaotic masses of electrons and ions moving at tremendous speed. This makes interstellar gas a conductor. If there was a time in the past when the Galaxy had no magnetic field of its own it was bound to appear. Owing to density and temperature gradients within them, the clouds are filled with continuously moving charged particles. Electrons overtaking the heavier ions create directional and vortex currents which induce a magnetic field in the Galaxy. At first its intensity is negligible, but then it begins to increase, and here is why.

The clouds of gas moving among the stars can be likened to a conductor moving in a magnetic field. In any moving conductor an electromotive force is induced which in turn creates a magnetic field of its own around the conductor. Clouds of interstellar gas carry such additional magnetic fields. The random motions of the gases result in the superimposition of the magnetic fields of different clouds, thus adding to the overall magnetic field of the Galaxy.

Magnetic forces act along the main "equatorial" plane of the Galaxy and the filaments of gas nebulae are drawn out mainly along it.

It is possible that the Galaxy even owes its spiral shape to magnetic forces. S. B. Pikelner, for example, has established not long ago that the extremely rarefied gaseous medium between nebulae attains velocities of tens of kilometres per second. At such speeds the particles of interstellar gas will recede appreciably in both directions from the mean equatorial plane of the Galaxy. Thus was discovered the Galaxy's spherical gaseous halo which surrounds the nucleus of our stellar system. All this is indication that cosmic magnetism plays an important part in the universe. The detailed study of this interesting phenomenon is only just beginning.

Now we can tackle the question of acceleration of cosmic particles. To begin with, acceleration can occasionally occur within a gas envelope itself. If a powerful shock wave propagates through the envelope, its velocity increases as the gas density decreases outward from the centre. With the density 10^{-8} g per cu cm, it becomes commensurable with the speed of light and the whole outer shell turns into cosmic radiation. When the shock wave reaches regions where the

density approaches ten-millionths of one gram per cubic centimetre particles with energies of up to 10^{17} eV can be produced, thus covering almost the whole spectrum of particles observed in cosmic rays.

However, there is reason to assume that in actual fact the maximum possible energy of particles accelerated by a shock wave is at least several orders of magnitude less. That is why today the most probable acceleration mechanism seems to be that employed in physical laboratories, that is, acting on charged particles with electromagnetic fields.

Firstly, there is so called betatron acceleration, when a particle is acted upon by a steadily built-up magnetic field. If the particle escapes the area of mounting intensity before the increase ends it carries off an energy increment.

Particles can be accelerated by making them collide with fast-moving "clots" of magnetic field. As a result a portion of the field's energy passes over to the particle, which can attain energies of 10^{17} eV. Although the process is slower than betatron acceleration it is effective during the particle's whole lifetime.

And one final question. Why are there more heavy than light nuclei in cosmic rays? Is it connected with the acceleration principle or is it because supernovae produce more heavy nuclei than other stars?

Scientists are inclined to see the main reason in the acceleration mechanism, especially at the initial stages. It is assumed that heavier particles are accelerated regardless of their initial energy, whereas for light particles to accelerate a certain initial energy is required, which many particles do not in fact possess. That is why cosmic rays contain more heavy nuclei than could be expected.

Thus, close to the earth an appreciable number of atoms of lithium, beryllium and boron have been observed, many times greater than their relative abundance in the universe. This is a result of the fragmentation of heavier nuclei in collisions with the atoms of the interstellar medium.

One of the basic characteristics of cosmic rays is their lifetime. This is what determines the fate of the galactic wanderers, which either leave the Galaxy or perish in collisions with nuclei of interstellar gas. (The interstellar medium we have been speaking of is made up of dust and gaseous matter 90 per cent of which is hydrogen. Its mean

density is 5×10^{-24} g/cm^3, which corresponds to approximately one hydrogen atom per cubic centimetre.)

The atoms of interstellar hydrogen are mostly neutral, but close to the galactic plane the hydrogen ionizes and becomes an electron-proton gas with a strong radio emission. The most probable concentration of interstellar gas is one particle per 100 cm^3 of galactic space. Given this concentration and relativistic speeds of cosmic particles it is possible to calculate their free run before a collision with protons of interstellar gas. It ranges from 140 million years for iron nuclei to 3,800 million years for protons. This is much less than the age of the Galaxy, which leads to the conclusion that cosmic rays did not originate together with the Galaxy but during its lifetime.

The possibility of cosmic rays leaving the Galaxy depends solely on the configurations of the magnetic fields and conditions at its boundaries. If all the magnetic lines of force are closed within the Galaxy cosmic rays become its eternal prisoners. However, according to available data, the Milky Way is not a "closed" system. Its lines of force extend into intergalactic space, where the magnetic field intensity is 100 times less than in the Galaxy, making it possible for cosmic rays to escape to other regions of the universe.

But the paths of most cosmic particles within the Milky Way are so long and tortuous that the time needed to travel them is usually more than the particles' lifetimes. Hence it can be confidently assumed that it is a fairly rare occasion for cosmic rays to escape from galactic systems, regardless of the structure of their magnetic fields.

Unlike charged particles, which in the course of their existence may span the length and breadth of the Galaxy back and forth for thousands of times, photons and neutrinos streak through it only once to vanish forever in the depths of the universe.

It is considered that at the present moment there are 10^{58}-10^{59} cosmic particles in the Milky Way. Their total energy is so great that it can be assumed equal to about one-half the energy of the Galaxy's magnetic fields.

Countless numbers of galactic wanderers enter the earth's atmosphere, carrying answers to important questions of astrophysics relating to the evolution and origin of the universe.

Let us go on with our story of contracting and expanding worlds, the creation of particles "out of nothing" and creative fields.

Alas, the state of our knowledge is such that the question still remains unanswered. All we can offer is two fantastic hypotheses, one belonging to D. A. Frank-Kamenetsky, the other to G. I. Naan.

Imagine that the universe is endless space, essentially flat and devoid of matter. Once in a while a tremendous fluctuation of vacuum occurs somewhere (vacuum, you will recall, is not absolute emptiness). The fluctuation manifests itself in the formation of a vast mass of neutrons and antineutrons, which causes a local curvature of space and its local expansion. In the course of the expansion particles and antiparticles annihilate and turn into light.

Chaotic turbulent motions develop on a stupendous scale. Space contorts and bends under the action of sudden concentrations of mass. Then, quite by chance, an excess of neutrons develops in some place, forming the embryo of a "world", a system of galaxies like ours. Somewhere else an excess of antiparticles forms, giving rise to an "antiworld" made up of antiatoms. "This fantasy," writes Frank-Kamenetsky, "shows vividly how interesting are phenomena in which both gravity and nuclear forces are simultaneously important."

There can be no doubt that science will eventually unravel the exciting mysteries of space and time—though never to the end.

Antiworlds, antimatter, antiparticles, annihilation of positrons and electrons; all these are rivers and rivulets flowing out of the Dirac ocean we have spoken of above. But the nucleus of Dirac's great theory is vacuum.

Dirac's vacuum is a sea filled with a great number of elementary particles with negative energies. We are incapable of detecting these particles with the help of our instruments, but if we impart them a huge energy potential we can "knock them out" of the vacuum. This is an intangible but quite material background in which our universe "floats".

But why "background"? asks G. I. Naan. Why not regard it as infinite, though invisible, world? It is a world that

moves and obeys all the dialectic laws of development. The fact that the energy of its particles is less than zero is of no consequence. It is analogous to algebraic operations with negative quantities. How do they differ from purely arithmetical operations? Only in respect of the negative sign.

None of our physical laws will lose their meaning. They will only be reversed as it were, acquiring the minus sign. And where the red shift of galaxies tells our astronomers that the universe is expanding, in the Dirac ocean the universe will be contracting and energy concentrating. Most important, the physics of bodies with negative energy is approximately the same as what the physics of bodies of our world would be in time flowing in the opposite direction. The intangible world lives in an opposite time direction, which is why it is intangible.

Our universe is eternally in the company of a time-reversed universe. Our "tomorrow" is its "yesterday". Both universes are mutually superimposed, they permeate each other, they coexist intangibly within us, though physically they don't affect each other in any way. Each one is a world of negative energies with respect to the other. It is unity and mutual negation, unity and struggle of opposites. It is the supreme expression of the laws of dialectics. The existence of a contracting and an expanding world is the source of development of the universe.

Perhaps there is no need to seek the "antiworld"—it is with us, within us, and intangible.

As yet intangible! Man's greatness manifests itself in active cognition of the unfathomable inexhaustibility of the universe. This inexhaustibility is exciting, enigmatic and beautiful. It is the researcher's greatest blessing that he can endlessly probe this inexhaustibility.

TOWARD THE NEUTRINO TELESCOPE

After our brief acquaintance with processes going on inside stars we return once again to the "ghost" particle. The neutrino's tremendous penetrating ability suggests that it might play an important part in cosmic phenomena. A study of the general neutrino radiation background could clear many points in the problem of the origin of our world.

These ideas provided the basis for the new branch of

science known as neutrino astrophysics, which treats of the many phenomena in which the neutrino plays the main part.

Neutrino astrophysics is one of the youngest sciences. It was born May 10th, 1960, at a session of the Cosmogony Commission of the USSR Academy of Sciences' Astronomical Council at which B. M. Pontecorvo and D. A. Frank-Kamenetsky submitted papers outlining the basic principles of the new science. At once, two main trends became apparent in neutrino astrophysics.

To begin with, the neutrino takes part in a number of nuclear reactions that are a part of the life processes of stars. Hence, as a theoretical science astrophysics must assess the neutrino's place in the dynamics of intrastellar processes. This may quite possibly require a review of certain cosmological concepts.

Furthermore, neutrino streams coming in from outer space can be recorded on earth, yielding invaluable information about the universe. This is the most promising and interesting sphere of neutrino astrophysics, which could be called experimental neutrino astrophysics.

For a long time the optical telescope was the only window into the universe. Man's contact with the greater world was restricted to the narrow range of optical wavelengths. Then radiotelescopes appeared, enabling him to extend the range of detectable electromagnetic radiation coming in from space. Then photography and bolometric measurements made it possible for man to listen in to the voice of the universe carried by previously invisible sections of the spectrum and further expand the observation range into the ultraviolet and infrared domains.

Add to this cosmic radiation, and the list of channels through which man maintains contact with the world of stars and galaxies is exhausted.

Thus, the bulk of information about celestial bodies is delivered to us by photons emitted from the surface of stars. Light and radio waves generated beneath the outer mantle of stars are absorbed by matter and cannot escape however intense they are. For that reason we can judge of internal stellar processes only from various theoretical models.

Now imagine what would happen if astrophysicists learned to record the intensity and energy of neutrinos and antineutrinos arriving from space and individual stars. In the

first place, they would obtain detailed information about processes going on inside stars, for neutrinos easily pierce the biggest stars.

True, other types of radiation may hamper neutrino registration. To get rid of it stars (our own sun in the first place) must be studied, in marked departure from conventional astronomy, not when they appear over the horizon but, on the contrary, when they are below the horizon and the interfering radiation can be absorbed by the earth as by a filter.

It is known that the sources of energy in stars are thermonuclear reactions of transformation of hydrogen into helium (the hydrogen chain and carbon cycle). But, as mentioned above, we can only speculate about the actual reactions. Neutrinos are capable of answering this question.

Neutrinos appear as primary or secondary products in different nuclear reactions, and their energies are directly dependent on the type of process in which they are created. This is the fundamental premise of neutrino astrophysics; the probability of interactions and, hence, of recording the ellusive particles is dependent on the neutrino's energy. The number of recorded neutrinos of different energies or, in other words, the energy distribution of the neutrino flux, provides information about the predominant type of reactions going on in inaccessible stellar interiors.

The energy emitted by the sun in the shape of neutrinos is fairly large, several per cent of the total. To gain an idea of the magnitude of this stream of energy it is sufficient to say that for thousands of millions of years our luminary has been spewing forth an energy equivalent of four million tons of mass per second. Thus, neutrinos carry away several hundred thousand tons of mass every second.

The primary task of neutrino astrophysics is to determine with sufficient accuracy the amount of neutrinos emitted by the sun. Neutrinos rain down on the earth in a steady stream. It is estimated that every second tens of millions of the ghost particles arrive per square centimetre. But the methods of detection in use are adequate only for even greater showers (of the order of 10^{12} particles per sq cm per sec). To register the sun's neutrino stream the sensitivity of recording devices must be increased at least a thousandfold. The hypothetical general background of "cosmic" neutrinos is smaller by another thousand times than the flux

of "solar" neutrinos, and it is not yet clear how so weak a background can be detected at all.

Neutrino astrophysics has one extremely important task in store. It is connected with the hypothetical existence of antiworlds. The only possibility of setting the question of whether galaxies and larger entities made of antimatter exist is to determine the ratio of neutrinos to antineutrinos. Such an experiment would also help solve another important cosmological question: are the amounts of matter and antimatter in the universe as a whole in balance?

At present workers are considering building a large subterranean laboratory for studying muon production by neutrino streams arriving from "down under" through all 13,000 kilometres of the earth.

THE MEGAWORLD

Neutrinos present an especially vivid example of the great unity of the world and the remarkable interrelationships between the processes going on in it. Without neutrinos we would never have been able to develop the modern theory of elementary particles; without neutrinos we cannot expand our knowledge of the universe. Two entirely different worlds, it would seem, with their peculiar measures of space and time, but in reality they are one. The universe is not only the Milky Way and stars but also atoms and elementary particles.

We have named these worlds and discussed them: the microworld, the macroworld, the megaworld. More exactly these worlds could be defined as domains characterized by sudden qualitative jumps in the gradual transition from the very small to the very big. For it is the new quality, the new physical laws that constitute the basis of this classification. We have already got acquainted with the peculiar laws of the microworld and had a peek into the megaworld. Now we are about to get more closely acquainted with the qualitative peculiarities of large quantities.

Formerly only a very small section of the universe was within reach of scientific investigation. In the days of ancient natural philosophy, in the days of the Renaissance man's units of measurement were few. Speaking in terms of modern measures, there were only centimetres or kilometres to measure length and seconds or years to measure time.

The first to be studied were the laws of the macrocosm. This is understandable. Man first studied his immediate environment and only then launched his quests into domains many millions of times larger and smaller than himself.

In his study of nature man discovered that at different levels the same interactions produce different results. No special instruments are needed to see this, there is no need to probe stellar interiors or atomic nuclei. Take, for example, such a concept as gravity. The force of gravity is a manifestation of the universal law of gravitation. It pervades all bodies and there is no evading it.

Transfer yourself mentally to Newton's time. We note with surprise that the smaller the mass the less the effect of gravity and the more important the forces of molecular cohesion. Water pours to the ground from a tilted cup, but a drop clings to the tip of a thin straw. Smaller drops float in the air, and the air itself, instead of settling to the ground, seeks to expand.

"Accustomed to a sphere of phenomena," writes B. A. Vorontsov-Velyaminov, "people often approach the study of a new domain by extending familiar images to it. The method of analogues and extrapolation in which familiar laws are extended to unfamiliar phenomena, plays an important part in science."

We saw above how Bohr and Sommerfeld represented the electron shells of atoms in the likeness of planetary orbits of the solar system. Then the model had to be rejected, as the new domain of phenomena is governed by laws of its own, the manifestations of which include quantized energy and wave properties of electrons.

It is most interesting that new properties and laws begin to appear after a relatively small change in the order of magnitude of a system. For example, the difference in dimension between systems possessing the property of life and governed by biological laws (man, animals, microorganisms) and molecules (10^{-8} cm), which are governed by molecular forces, is six to ten orders of magnitude. The difference between the dimensions of molecules and atomic nuclei (10^{-13} cm) is only five orders of magnitude.

Neither quantum processes nor nuclear forces could be predicted on the basis of knowledge of the laws of gaseous states or cellular fission. Similarly, we cannot predict what

physicists will find when they overcome distances of 10^{-14} or 10^{-15} cm.

From his place in the universe, from the dimensions of his system, man has descended 15 orders of magnitude into the microworld. On the way he has encountered a breathtaking variety of biological, molecular, atomic and nuclear phenomena.

Now let us direct our attention to the other end of the scale and embark on as remarkable a journey from the macroworld into the megaworld. In the megaworld man has reached out to systems such as galaxies which exceed his own system by 20 or 21 orders of magnitude. In the megaworld millions and thousands of millions of kilometres are unsuitable as units of length. Here one must deal with units like the light-year (10^{13} km), parsec (3×10^{33} km), kiloparsec (10^3 parsecs) and megaparsec (10^6 parsecs). The duration of processes in the megaworld, as we know, can be measured in thousands of millions of years, and velocities are frequently commensurate with the speed of light. It is interesting that velocities in the microworld and megaworld can be measured in quantities of the same order of magnitude, setting them both aside from the macroworld which knows no such great velocities. The megaworld is a world of gigantic cosmic systems the totality of which constitutes a system of the highest known order of magnitude, what we call the metagalaxy.

The idea that there exist stellar systems outside the Milky Way was advanced back in the 18th century by Immanuel Kant and the English astronomer Thomas Wright. Wright thought that, just as there are other suns besides our own, so there are other stellar systems besides our Galaxy. This great scientific prophesy was based solely on the method of analogues. Kant considered these stellar systems to be so remote that no telescope could resolve them into separate stars. Also on the basis of the method of analogues, Kant predicted that "island universes" should appear as dim blobs of light, circular or elliptical in shape, depending on their inclination to the line of sight. These blobs, which were called nebulae, were discovered by many astronomers, but none of them was able to show that they lay outside the Milky Way.

The history of extragalactic discoveries commences with William Herschel. His most outstanding contributions in-

cluded investigations of the nature of nebulae. The difficulties of his task were aggravated by a terminological muddle, since the word "nebula" was (and occasionally still is) applied to both extragalactic objects and glowing masses of diffuse matter within our own system. Even thirty or forty years ago our notions of nebulae were highly inaccurate and contradictory.

In 1785, Herschel came to the conclusion that nebulae represented optically unresolved images of stellar associations lying outside the Milky Way.

However, eighty years later William Huggins, a pioneer in astronomical spectroscopy, showed that the light from the Orion and certain other nebulae was identical to the radiation of glowing masses of gas. It thus worked out that nebulae were no more than clouds of gas and in no way of extragalactic origin.

In 1845 a new reflector telescope with a six-foot mirror was installed in Ireland. Using it, Rosse made one of the most outstanding astronomical discoveries of the 19th century: the spiral structure of some nebulae. The discovery of the first spiral nebula in the constellation Canes Venatici (Hunting Dogs) ushered in a new era in cosmogony. Quite a few such nebulae were discovered during Rosse's lifetime, and by 1918, when the famous reflector on Mt. Wilson was built, their number ran up to half a million. Yet even then many astronomers were inclined to regard spiral nebulae as galactic objects.

In 1885, a star was discovered in the Andromeda spiral-shaped nebula. It flared up suddenly until its luminosity reached one-tenth that of the whole nebula. Its position in the nebula and its spectrum, which differed substantially from a typical nova, showed clearly that it was not a nearby star lying in the line of sight of the nebula.

Only thirty-odd years later, when a photograph of the nebula was carefully studied, were two new, very weak stars discovered in it. This led to the conclusion that the Andromeda lies some one million light-years away and that its size is comparable to that of the Milky Way.

In 1924, E. Hubble (of the "red shift") showed that the Andromeda nebula is the closest galaxy to us in which a supernova had exploded in 1885.

Modern telescopes have been used to photograph hundreds of galaxies. In some sections of the sky there are even more

galaxies than stars. In the pictures the galaxies appear as nebulous, slightly washed-out blobs. But when the negatives are viewed through a microscope the blobs resolve into "island universes" of different types.

In 1956, American astronomers completed a unique atlas of the sky. It comprises a vast number of photographs of different sections of the sky made with the help of the 48 inch telescope at Mt. Palomar observatory. Thousands of hitherto unknown stellar systems were revealed to the wondering eyes of man. A study of all these systems is a task which will occupy many years to come. But the first results have already served to radically alter our idea of the megaworld. At present more than a thousand million galaxies are known to exist. They differ in structure and size. Distances between them average 500,000 parsecs. It takes a beam of light a million and a half years to span the distance from one galaxy to another. Intergalactic space, like interstellar, is pervaded with an extremely tenuous medium and also contains stars "thrown out" of galaxies.

Our Milky Way is a very common little island in the metagalactic system only a portion of which is accessible to optical and radio telescopes. This is known as the "astronomical universe".

But although no man has yet been able to see the boundaries of the metagalaxy, it was discovered long before modern telescopes appeared. Just as in its time the great foresight of Democritus and Leucippus had anticipated by many centuries the development of atomistics, so the man who discovered the metagalaxy anticipated his time.

ARCHIPELAGOS OF ISLAND UNIVERSES

It was a time when William Herschel was only just dreaming of studying the stellar world. It was an age when the boundary of the solar system lay at the orbit of Saturn. It was then that, contrary to all the learned theories of his contemporaries, Johann Lambert discovered the metagalaxy.

Lambert was a disciple of Giordano Bruno, who also vocally declared, contrary to all canons, that stellar worlds were countless in number, for which he was burned at the stake. Lambert was sure that, just as the sun has its family of planets, every star has planets revolving around it.

According to his ideas, all planetary systems together with their suns represent the first step in the hierarchy of the world, they are systems of the first order. Stellar associations which we today call galaxies are, according to Lambert, systems of the second order.

Calling upon an analogy, a fruitful method but not without pitfalls, Lambert expressed the view that systems of the second order should form larger third-order systems, and so on, *ad infinitum*. Science is only just beginning to probe the third-order system, what we today call the metagalaxy. It is impossible even to speculate about higher systems, and not because contemporary science is lacking in vision. The world is not as simple as it may have appeared to Lambert. In his hierarchy of systems one system resembles the other like a series of nested dolls. Today we know that quantitative growth is accompanied by profound qualitative changes. Galaxies are quite unlike planetary systems, and stars differ from either planets or galaxies. Where the motions of planets are governed by a central star whose mass exceeds the combined mass of all the planets, the centre of a galaxy does not contain, contrary to Lambert, a gigantic star.

The relative density of galaxies in space is greater than that of stars. The mean distances between stars are seven or eight orders of magnitude greater than their diameters; intergalactic distances exceed galactic diameters by only one order of magnitude. Are we entitled to extrapolate these ratios to higher systems and say that metagalaxies are relatively more densely packed than galaxies? All we can say on this score derives from the laws of dialectics. Metagalaxies, if there are any besides the one we know, must differ from galaxies both quantitatively and qualitatively.

What do we know of galaxies?

Edwin Hubble, a pioneer of metagalactic studies, distinguishes three main types of galaxies: elliptical, spiral, and irregular. Formerly it was thought that the spiral form predominated among extragalactic nebulae, but lately it has been found that elliptical nebulae are more numerous. They differ markedly from spiral galaxies. They have no spiral arms and, furthermore, contain little or no dust or dark absorbing matter. A photograph of an elliptical nebula does not at first glance look like a stellar system.

It is rather like a glowing galactic nebula, except for its well-defined elliptical shape. They also come in a wide range of elliptical shapes, from a regular sphere to a flattened lens.

As distinct from elliptical galaxies, spiral galaxies have a prominent spherical nucleus and a flattened external part with more or less clearly defined spiral arms.

Irregular galaxies show no definite shape. The closest to us are the two "satellites" of the Milky Way known as the Magellanic Clouds. They were first described by a participant in Mageellan's voyage around the world.The Magellanic Clouds are made up of tens of thousands of stars, more than 2,000 of them variables, and lie 125,000 light-years away. The Large Cloud has a diameter of about 26,000 light-years, while the diameter of the Small Cloud is about 17,000 light-years.

Together with the Milky Way the Magellanic Clouds form a dynamic system of three galaxies. The Large Cloud is connected with the Milky Way by a vast stellar corridor.

Galaxies vary greatly in size, spiral galaxies being generally larger than elliptical. The celebrated Andromeda nebula has a diameter of about 40,000 parsecs, which makes it slightly larger than the Milky Way. A galaxy in the Triangulum constellation is only 7,000 parsecs across.

Depending on their size, galaxies may contain anywhere from 10^7 to 10^{12} stars, and their masses are estimated respectively at 10^{42} to 10^{45} grams. Small galaxies are much more frequent than giants. Several spherical "dwarf" galaxies of the Sculptor type have been discovered in the vicinity of the Milky Way. They are sparse, with relatively few stars.

In 1924-1926 Hubble resolved the outer parts of the spiral-shaped Andromeda nebula into stars, thereby demonstrating the existence of gigantic stellar systems. In 1944-1945, Walter Baade resolved the galaxy's nucleus and also showed that elliptical galaxies contain only stars, with no traces of gas or dust. In later years, however, B. A. Vorontsov-Velyaminov discovered several elliptical galaxies containing dust and gas.

In 1944 Baade plotted a spectrum-luminosity diagram for bright stars in the nucleus of the Andromeda nebula and the Triangulum galaxy Messier 33. He found that the upper end of the curve coincided with the curve in the

diagram for stars of globular clusters within our Milky Way. At the same time, the spectrum-luminosity curve for stars in the neighbourhood of the sun was found to be markedly different. Thus the stellar "population" of galaxies was classified into two types. Population I is found only in the spiral arms of galaxies and is always mixed with population II stars. Population II stars are typical of elliptical galaxies. It has been found, significantly, that stellar populations of other spiral galaxies generally follow the same pattern as the population of the Milky Way. Irregular galaxies are made up wholly of population I stars.

G. A. Shain and V. F. Gaaze have also discovered in neighbouring galaxies stellar associations similar to those found in the Milky Way, additional confirmation that it is in no way outstanding among other galaxies of the astronomical universe.

Besides electromagnetic waves of the optical bandwidth, galaxies also emit radio waves. As a rule galactic radio emission is fairly weak; however, there are systems like the radio galaxy Cygnus A whose radio emission is hundreds of thousands of times higher than the average.

V. A. Ambartsumyan has discovered that some elliptical galaxies have satellite galaxies that emit blue light. It is assumed that the light of blue galaxies is due to continuous radiation. Astronomers consider blue galaxies to be the youngest known stellar systems.

Galaxies show an interesting tendency to form groups and clusters. It seems probable that the "island universes" originated in clusters. There are very few lone galaxies. The overall distribution of galaxies is highly erratic, a feature of metagalactic structure which remains unexplained.

The nearest and most apparent galactic cluster is in the constellation Virgo. It has about 500 stellar systems and its diameter is of the order of millions of parsecs. A cluster in Coma Berenices contains 10,000 members. Some workers consider that the local galactic system, which includes the Milky Way, the Andromeda nebula, the Magellanic Clouds and ten other members, is part of a "family of nebulae" which the French astronomer G. de Vaucouleurs calls the supergalaxy. It comprises a vast number of galactic clusters of different size and includes thousands or perhaps even tens of thousands of galaxies. The cluster in Virgo is the dense central part of the supergalaxy. A some-

what smaller supergalaxy has been discovered in the southern hemisphere. Supergalaxies are estimated to be 30 to 40 megaparsecs in diameter.

Galaxies frequently form double or multiple groups extending for 10 to 50 thousand parsecs. Thus, the Andromeda galaxy is a multiple system of five members. In V. A. Ambartsumyan's view most multiple galaxies are trapezoid systems, which is an indication that galaxies are formed in groups and that the process is going on at present.

In the early stages of their existence galaxies are evidently unstable, as exemplified by radio and blue galaxies.

Finally, observed eruptions of matter from the nuclei of some galaxies, as well as the observed strong outflow of gas from the nucleus of our own system, where its density should not be great, indicate the possible existence of highly dense formations within galactic nuclei the disintegration of which produces the phenomena.

This idea is in line with the views of Ambartsumyan, who considers that galaxies, like stars, evolve from superdense to less dense states. This so-called contemporary observational school in galactic cosmology contradicts with the classical school expounding the ideas of James Jeans about the formation of galaxies through the condensation of rarefied gas. Hypotheses of the classical school have been enunciated by Hoyle, Weizsäker, Oort, Baum, Gurevich and Lebedinsky.

The origin of galaxies remains a riddle. It is still equally hard to say whether galaxies and clusters have existed in perpetuity (there is such a view, too), whether they were formed as a result of condensation of primary cosmic gas in the early stages of the evolution of the world, or, finally, whether they formed on disintegration of some superdense protomatter. There is somewhat more available background data about the formation of stars than galaxies, though there are grounds for assuming that both problems are closely related.

Many observational data indicate that at present star formation processes are taking place only in irregular galaxies and in the arms of spiral galaxies, where there are large quantities of dust and gas which can condense into stars (if that is how stars are made).

An interesting suggestion has been made that a spiral galaxy is an irregular galaxy revolving within an elliptical

one, which explains the spiral shape. When such a typical spiral galaxy as the Andromeda nebula is photographed in infrared light its spiral arms become invisible and the galaxy itself has the shape of a small spherical system. This indicates that the spiral arms, which find their way into ordinary photographs thanks to the luminosity of the stars in them, are perhaps only secondary appendages. This is all the more interesting as there are grounds for regarding spiral arms as comparatively short-lived formations. Spectral investigations of light from different sections of the arms indicate that they are revolving around the central nucleus. That being the case, the spirals must inevitably merge as the velocity of rotation is dependent on the distance from the centre and the external regions are revolving slower than the internal ones. This is in agreement with observational findings. Occasionally the galactic arms are found to be wrapped two or three full turns, an apparent indication of their young age.

The classical hypotheses fail to explain the origin of multiple systems. Many researchers, notably the Swede E. Hallberg, hold that multiple systems are no more than the fortuitous results of meetings of formerly independent galaxies. It is difficult to accept this view, if only because lone galaxies are found fairly rarely (it is interesting that among stars single systems predominate). On the basis of observations of multiple and, especially, interpenetrating and interacting galaxies, Vorontsov-Velyaminov rejects the notion of fortuity in the formation of galactic associations, holding that they must be of one origin. He comes to the conclusion that there are unknown forces which manifest themselves in the large-scale evolution of galaxies. His views are especially interesting as they represent a first attempt to reveal a new quality appearing in the transition from the macroworld to the megaworld.

NEWTON'S LAW OR METAGALACTIC FORCES?

Like all fundamental problems of the world, the argument about the finality or infinity of the physical universe dates back to deep antiquity. Aristotle considered the physical universe finite, while the ancient atomists were sure that atoms filled infinite space.

Lucretius wrote in his *De Rerum Natura*, "Space has

neither end nor limit and extends infinitely and uniformly in all directions." In the Middle Ages, when Aristotle's teaching was accepted as the ultimate truth, the idea of the finality of the universe prevailed. The first astronomer to declare that the stars were like our sun and scattered in infinite space was the Englishman Leonard Digges (1576). This concept was brilliantly advanced further by Giordano Bruno.

Newton's theory of universal gravitation proceeded from the notion of an infinite universe. Newton considered that a finite universe in inifinite space would inevitably be contracted by its own gravitational forces into a compact body. In a letter to Bentley in 1692 he stated, "But if the matter were evenly distributed throughout our infinite space some of it would convene into one mass and some into another, so as to make an infinite number of great masses, scattered great distances from one another throughout all that infinite space." It derived naturally from this that the law of gravitation must be a universal law. Subsequent investigations by Herschel confirmed the validity of the universal law beyond the confines of the solar system.

The first man to express doubt that Newton's system could be extended throughout the whole universe was the German physicist Neumann (1874). Ten years later his compatriot, the astronomer Seeliger, indicated a weak point in Newton's system. Proceeding from the notion of uniformly distributed matter in infinite Euclidean space, Seeliger began by assuming that all matter is located within a sphere of radius R and that its mass is proportional to the volume of the sphere. At any point on the surface of the sphere the gravitational force, then, is proportional to the square of the radius. If Newton is right and the universe is infinite, Seeliger reasoned, its model is a sphere of infinite radius. But in that case the gravitational force at points infinitely far from the centre should also be infinite. And as the centre of an infinite universe can be chosen at random, it obtains that the gravitational force should be infinite at any point, depending on the randomly chosen centre. This was a logical paradox. To evade it Seeliger suggested that at very large distances Newton's law was in need of a correction factor.

What is the situation today? For systems more complex than double or, at best, multiple stars the validity of the

law of gravitation has not been tested. Already in the case of scattered associations of several dozen stars we have no way of being sure that other, more powerful, forces do not operate alongside Newton's.

In their attempts to establish whether this is so or not astronomers come up against extreme difficulties. In studying stellar associations and galaxies they do not observe star orbits as such. At best they know only the instantaneous velocity in the direction of sight. For that reason, in putting forward their ideas on the origin, evolution or dynamics of stellar systems, scientists have to invoke concepts derived from the solar system or even the microworld. Which means transferring specifically macro- or microproperties into the megaworld. There exists, for example, an explanation of giant stellar associations in terms of totalities of mutually attracting material points, reducing the general properties of the system to mutual gravitation between points. In adopting such a stand one inevitably loses sight of the qualitative features that manifest themselves in a sum of individual entities.

A widely used analogy likens stars to gas molecules and the passage of stars in close proximity to one another to molecular collisions with their resultant redistribution of energy between the bodies involved. Interestingly, some researchers endow this stellar "gas" with viscosity, others declare it nonviscous.

"It is hard to check this," writes Vorontsov-Velyaminov. "Reference to the observed shapes of stellar systems (and not processes, which we cannot observe) is not reliable enough. As is known, the same fact is frequently interpreted as confirmation of the most divergent theories."

As an example we could take the cluster of hot stars known as object NGC 2244 in the constellation Monoceros. It is surrounded by a gaseous ring-shaped nebula with a dark spot at the centre. Several explanations of this phenomenon have been offered. 1. The stars condensed from the gas in the central part, which was once dense and has by now been exhausted. 2. Stars straying into the nebula absorbed its gas. 3. The stars expelled gas, which we see as receding from them. 4. The pressure of light and thermal radiation from the stars, which formed from cosmic dust and meteoroids, forces the gas away. 5. Stars and gas originated together and independently out of some pres-

tellar matter. 6. The interstellar gas is invisible owing to changed physical conditions around the stars.

Since the same fact can serve as experimental confirmation for quite different hypotheses, the Arend-Roland comet with its two oppositely directed tails, which appeared in 1957, gave rise to a spate of different explanations of the phenomenon.

Already Herschel and Rosse had described mysterious nebulae with double nuclei or connected by long corridors. For decades the English astronomers' sketches were a source of speculation and debate. Only recently have astronomers turned their attention to queer dumbell-shaped galactic objects.

Zwicky regards various observed galactic appendages and connecting corridors as intergalactic matter. This makes it possible for him to claim that the space between galactic systems is not empty and the average density of matter in it is higher than can be expected when only galactic masses are taken into account.

On the other hand, de Vaucouleurs, who discovered a dimly glowing appendage jutting from the Large Magellanic Cloud away from the Milky Way, is inclined to regard it as a tidal prominence. These and similar observations were investigated by Vorontsov-Velyaminov, who came to some remarkable conclusions.

The scientist was struck by effects which defied explanation in terms of gravitational law. One thing appeared strange. Whereas there could be no doubt that the Magellanic Cloud had a jet or appendage extending away from the Galaxy, the existence of a corridor between the Cloud and the Galaxy still had to be proved. Photographs of pairs of galaxies obtained by Zwicky showed jets, but no prominent tidal bulges or corridors.

What could be the matter? If the tidal prominences are caused by gravitational forces the "front" and "rear" bulges should be more or less the same. The only assumption could be that other forces are involved. But what?

Studying the atlas of Mt. Palomar observatory, Vorontsov-Velyaminov found no less than 500 interacting galaxies which could have originated only together and not be a result of fortuitous collisions. Moreover, the distorted shapes caused by the galactic interaction seemed to indicate that, although gravitational forces are present,

the visible results of the interaction are in no way due to them.

"It thus appears," writes Vorontsov-Velyaminov, "that for the first time we are faced with qualitatively new properties and forms of interaction of large systems in the megaworld."

These new properties manifest themselves together with gravity, but it is possible that in some cases they are the dominant components. What galaxies can be regarded as interacting?

The first characteristic of interaction is distortion of the normal shape, such as the development of appendages, jets, corridors. Some neighbouring galaxies float in a glowing mist like several planets in a single atmosphere. The Magellanic Clouds, for example, are enveloped in an invisible atmosphere of hydrogen. But these are only visible manifestations of interactions. If we could get more detailed information about invisible neutral hydrogen the number of interacting galaxies would increase sharply. It has been suggested that a common hydrogen cloud envelopes the Milky Way and the Magellanic Clouds (they are farther from the Milky Way than from each other). Radio-astronomic data indicates that a thin layer of diffuse gaseous matter is tilted from the equatorial plane in the direction of the Magellanic Clouds. Such a tilt, due undoubtedly to galactic interaction, has been observed in other galaxies.

It is thus apparent that interacting galaxies are not a work of chance but a natural stage in the evolution of the megaworld. The number of optically observable interacting galaxies approaches five per cent of the total number of island universes, a clear indication of their joint formation.

As a rule the distance between interacting galaxies is smaller than their visible dimensions, though in at least one case it is several times greater than the diameters of the interacting members.

There are several pairs of galaxies which, in spite of their proximity, display no apparent distortion of shape, although many more distantly spaced galaxies are substantially deformed. This is a peculiar observation which may be due to nongravitational interaction.

The most frequent manifestation of mutual interaction of galaxies are extended jets which are often longer than the galaxy's diameter and are directed away from the per-

turbing system. The connective corridor is usually not very pronounced, reduced to bulges or absent altogether. The observable picture seems to be that of repulsion of at least a portion of the galaxies' matter. Neither corridors nor jets can be explained in conventional terms of gravitational tides, which could cause no more than short conical projections brighter at the base, where there is more matter.

The existence of double corridors also speaks against the tidal nature of perturbations in galactic shapes. A corridor may represent thin filaments extending between interacting galaxies, and the filaments themselves may be different within the same interacting system: straight or twisted, which cannot be explained by tidal action.

Sometimes a corridor may at the same time be a spiral arm of one of the interacting systems. An example is a not-too-distant galactic couple known as NGC 5194-5 in which a large spiral galaxy has extended one of its arms toward its smaller companion. Until fairly recently astronomers had regarded this as a fortuitous superimposition of one galaxy on the spiral arm of another. But Vorontsov-Velyaminov has discovered several other such systems. He has also discovered that some corridors between galaxies contain blue condensations of hot stars.

All this is testimony that galactic corridors, jets and spiral arms are made up of the same material, hot stars. This conclusion was independently arrived at by the Americans Zwicky and Carpenter on the basis of spectral observations.

The similarity in composition is evidently not fortuitous and indicates similar origin.

Spiral arms consist mainly of stars, with gas accounting for one-tenth of the total mass. This is explained by the fact that, after the formation of a stable gaseous spiral arm, the gas gradually condenses into hot giants.

If that is the case, then we should concede that the spiral arms are about as old as the galaxies. On the other hand, if spiral arms were short-lived formations they would not be observed in the closer galaxies as well as in those which we see in the state they were thousands of millions of years ago. Nor can we assume that spirals began to form on the periphery of the astronomical universe and appeared close to us only recently. There are no grounds for this. Hence, it must be assumed that spiral arms and other elongated

stellar formations must possess some kind of viscosity that makes them stable. Zwicky, in studying multiple galactic systems, also arrived at the notion of the greater viscosity of galactic nuclei, and this is confirmed by a number of other observations.

Elliptical galaxies, which are thought to be very old, also display corridors and jets. Nongravitational interactions have also been observed between small families of galaxies.

Thus in investigating the nature of galactic interactions we find that, though the component stars are undoubtedly linked by gravitational forces, the galaxies themselves may perhaps be connected by some mighty hitherto unknown forces.

TRACES OF PRESTELLAR MATTER

Like nuclear physics, extragalactic astronomy is currently going through a period of "change of ideas". We have already seen how hard it is, if not impossible, to fit many newly discovered facts in the narrow limits of traditional concepts. Scientists can no longer get along without new and unusual ideas capable of satisfactorily describing observed cosmic phenomena.

A review of all past cosmogonic hypotheses reveals that they share one dominant idea in common. It was first expressed in remote antiquity and is reflected in the Bible. From Chaos to Cosmos, from disorder to order—is the assumed evolution of the universe. It is only natural, therefore, that the origins of celestial bodies are seen as condensations of a primordial chaotic nebulosity. In effect the whole of cosmology is a collection of variations of the same scheme.

It always seemed obvious that cosmic entities evolve from bodies of low density to bodies of high density. A steadily ascending spiral. And what then? Apparently decline, disintegration which reduces the celestial body to the initial state of chaos. Then concentration of matter again, and again disintegration. And thus forever, endlessly in time, infinitely in space. There was a certain logic to the scheme.

A protonebula condenses into galaxies in which titanic fluctuations emerge as stars. The huge masses compressed

in the stars spark thermonuclear reactions. The stars hurl streams of energy, vast clouds of gas, showers of corpuscles into space, all of which is a source feeding the formation of new stars.

But gradually this "self-evident" scheme of recycling of matter began to appear primitive. And not only because it seemed to leave no place for planets, numbered in thousands of millions in the Milky Way alone. Unanswered remained the question of what happens to the stars that have exhausted their energy reserves.

As in the millions of years of its existence as a luminary, a star loses only a few percent of its mass, it remained unclear how the "self-evident" schemes could explain the recycling of matter without taking "burnt-out" stars into account. But perhaps the scheme is on the whole correct, lacking only in comprehensiveness. Perhaps it only has to be supplemented with burnt-out stars or some other form of matter, such as prestellar matter?

In 1947, Ambartsumyan discovered stellar associations and came to the conclusion that their component luminaries evolve at the same time.

What remained unexplained was the character of the prestellar matter which had gone into their making. One thing was clear, namely that conventional forms of matter are unsuitable for the purpose. Thus began the long quest for prestellar matter.

The members of a stellar association are acted upon by certain forces (we shall leave aside their nature) emanating from other stars of the galaxy, which cause them to disperse fairly quickly. Hence, the associations we observe today are fairly young formations.

This is a repetition, in miniature, of the picture of fleeing galaxies. Some associations are observed to be expanding quite perceptibly, their stars flying apart from their common centre at speeds of five to ten kilometres per second. The obvious conclusion is that in the past stellar associations were much more compact, and they must have originated in a fairly small spatial domain.

The speed with which the stars are scattering offers a clue to the speed of disintegration of the association, and the calculations carried out by astronomers have yielded an astonishing result: whereas the sun is at least several thousand million years old, stellar associations are "only"

one to five million years old. As in the atomic world, in the world of stars we also find "long-lived" and "short-lived" entities.

What have stellar associations appeared from?

Traditional notions about nebulae must be rejected outright. To begin with, there is no direct proof that nebulae can condense into stars at all. On the contrary, it is well known that stars can and do spew gas into space. In some associations symmetrically shaped nebulae can be seen expanding from the centre. Perhaps it is not quite right to pose the alternative: do nebulae precede stellar associations or are they, on the contrary, a product of their evolution? The truth may lie somewhere in between. There are indications that nebulae and stellar associations submerged in them appeared together out of a stable prestellar matter which was neither stellar nor nebular and, in any case, has never been observed.

Protostars, as Ambartsumyan calls the bodies out of which stellar associations are born, must, in the first place, possess enough matter to make the nebula and several scores of stars. If they were dispersed, rarefied entities they would cover large areas and be observable in a telescope. As this is not the case one must assume that protostars are very small, very massive, and hence very dense bodies. Furthermore, they must possess stupendous potential energy reserves to feed the spectacular explosion capable of fathering an association of stars.

Thus appeared a new cosmogonic concept which is diametrically opposed to the Chaos-to-Cosmos formula. In Ambartsumyan's view stellar evolution from birth to "maturity" is from a superdense state of matter to much less dense states.

As we have seen, galaxies display an even greater tendency to associate than stars. True, if the world of galaxies, the megaworld, obeys the laws of stellar worlds it does so on a much higher level and on a much more spectacular, qualitatively new scale. Where the age of a "young" stellar association is measured in millions of years, the age of "young" galaxies must be reckoned in thousands of millions.

Astronomers have discovered such "young" galaxies. They occur in groups clustering around a common centre of mass. The perturbation effects between them are so

great that the group disintegrates after just a few revolutions and the galaxies are "lost in the crowd", just as happens with stellar associations. The analogy between galactic groups and stellar associations can be extended still further, as groups of galaxies also tend to expand.

An example of such expansion is presented by a group of galaxies known as Stephan's quintet. Four of its five systems are "fleeing" from the earth at a rate of around 7,000 km per sec while the fifth is receding at only around 1,000 km per sec. This means that it is receding from the rest at approximately 6,000 km per sec, a truly explosive velocity.

Zwicky investigated a group of three galaxies one of which is separating from the others at an even higher speed. Other examples of "exploding" systems are also known.

Perhaps the colossal galactic forces postulated by Vorontsov-Velyaminov are the cause of the expansion of some galactic groups. A determination of the velocities of some of the closer galaxies reveals that they cannot be explained in terms of the law of universal gravitation alone. The galaxies are moving under the action of unknown forces of colossal scope.

If we accept the idea of the joint origin of interacting galaxies we must assume that the formation of "island universes" also involved the liberation of a formerly latent energy. Thus, here too we arrive at the idea of a hypothetical prestellar, perhaps even pregalactic, matter containing stupendous energy reserves. There are, however, not many facts which could be interpreted as direct manifestations of prestellar energy.

One of them is the strange shape of the galaxy NGC 4486 in Virgo. It demonstrates a powerful jet with alternating condensations and rarefactions of matter erupting from the nucleus. The blue colour of the condensations indicates that the radiation is caused by relativistic electrons. Assuming that the nucleus of NGC 4486 consists of only stars and nebulae, it is impossible to explain the eruption. Suffice it to say that the mass of the blue clots of matter in the jet approaches the mass of a minor galaxy.

Perhaps unknown mysterious forces are raging in that remote stellar island and prestellar matter in the galactic nucleus is churning in a stream of relativistic particles as it gradually evolves into familiar forms of matter.

Something similar can be observed on photographs of the galaxy NGC 3561, which has a jet containing a blue clot with a mass of millions of suns.

Even at the centre of our closest galactic neighbour, the Andromeda nebula, astronomers have discovered a spherical nucleus some 16 light-years in diameter. It is suggested that the mass of this nucleus must be very great indeed. Ambartsumyan considers that it is made up completely of protostars, which would explain its relatively low luminosity as compared with its tremendous mass.

A similar nucleus has been discovered within our own Galaxy. The spectra of galactic nuclei indicate that they are surrounded by eddies of gas continuously erupted from them. It is a domain where fields are created and destroyed, where matter is continuously being transformed from one state to another, where stars and nebulae are being formed out of prestellar matter.

In these crucibles of universes primordial bodies undergo mysterious changes after which they proceed to evolve into galaxies.

Ambartsumyan considers that the ejection of a small galactic "embryo" from the central nucleus of a giant galaxy can be regarded as an example of "galactic fission".

The remnants of stellar matter in the nuclei of galaxies that have already split may, perhaps, originate new eruptions of matter and new fission processes.

Only an incomprehensibly large mass of prestellar matter can retain a degree of stability in which the accumulated energy is as it were closed in on itself and therefore remains latent. This is a "supercritical" mass which is so great and dense as to make decay impossible.

When the "supercritical" nucleus for some reason loses its stability and vast streams of energy break loose with the speed of chain processes the fragments of prestellar matter that appear in the process cool gradually, turning into nebulae and stars.

This, in brief, is the scheme of the birth of worlds out of prestellar matter offered by Ambartsumyan. It is still a tentative theory, the basic framework has not yet been covered with the flesh of facts and, like all our notions, it is true only at a certain stage of cognition. The development and triumpth of this idea will at the same time spell its doom. It will become no more than a special case,

a more or less authentic detail of some titanic process of even greater complexity and depth.

What real facts or theoretically trustworthy conceptions enable us to speak of superdense states of matter? We already know of some: white dwarfs and neutron and hyperon star models.

Perhaps hyperon stars are capable of suddenly changing their inner state thanks to which boundless oceans of energy are released. True, the hyperon star model is but a remote approximation of what we speak of as protostars. But the world is an integral entity and knowledge of the mysteries of superdense states is a road to the secrets of prestellar matter. Nor is it the only road. Matter is inexhaustible, and inexhaustible are the diverse forms in which it manifests itself. The quest for new types of energy and states of matter, the quest for unknown spatio-temporal forms is a long-term, never ending quest. It began at the dawn of the human race and it will continue endlessly as one generation succeeds another.

BRIGHTER THAN A MILLION SUNS!

In 1960, California astronomers discovered that the coordinates of a celestial radio source denoted 3C 48 according to the 3rd Cambridge catalogue coincided exactly with the position of a telescopic star within a sparse nebula. When they obtained the distant sun's spectrum the scientists were struck by the very unusual combination of absorption and emission lines. The hydrogen lines, so common in conventional stellar spectra, were absent altogether. This was quite inexplicable.

There were no other objects within the star's vicinity to which the radio emission or strange spectrum could be related. There could be no doubt about the star's identity with the radio source. The astronomers decided that they had discovered the "first genuine radio star". A report to the effect was released to the press. The assumption that 3C 48 was the remnant of a newer and more distant supernova than the famous star of 1054, of which the Crab nebula remains a spectacular reminder, seemed logical enough. It surprised no one. Yet the mystery of the strange spectrum remained.

Not much time passed before another point radio source,

3C 286, was also identified with a distant star possessing a remarkable spectrum. When, after an exposure of several hours, workers at Mount Palomar finally obtained the spectrum they discovered only two absorption lines, one weak and broad, the other exceptionally bright at $\lambda=5170$ Å. This line had never been observed in any supernova, planetary nebula or even in the sun's corona.

As time passed the astronomers continued to locate radio sources coinciding with visible stars, notably 3C 147 and 3C 196.

Hopes of solving the mystery were bolstered after the discovery of a new point source, 3C 273, which was identified with a bright star in Virgo. A thin nebulous filament was observed next to the star. At first there was difficulty in deciphering the series of emission lines in the spectrum. But then, in March 1963, the young Dutch astronomer Maarten Schmidt made the bold suggestion that the mysterious lines in the star's spectrum were neither more nor less than the very ordinary Balmer series of hydrogen lines. Their anomalous position was explained simply enough: they were shifted to the red end. But if this was the ordinary red shift due to the Doppler effect, then the stellar object must be receding from us at a velocity approaching 50,000 km per sec. The large red shift hypothesis provided the key for deciphering the 3C 48 spectrum. Its mysterious lines were identified with the prohibited lines of neon and oxygen and the double line of ionized magnesium. Only in this case the speed with which 3C 48 is receding works out to 90,000 km per sec, one-quarter the velocity of light!

The red shift was clear indication that the radio stars are extragalactic objects lying at tremendous distances. Thus, the distance between us and the "oldest" radio star, 3C 48, is 4,000 million light-years. This was incomprehensible. The remotest galaxy discovered by 1963 lies 6,000 million light-years away. But that, after all, is a galaxy, while 3C 48 is only a star.

Doubts were voiced. After all, the red shift, as we know, can be a consequence not only of the Doppler effect, but of the Einstein effect as well. From relativity theory we know that the red shift in a star's spectrum is proportional to the star's mass and inversely proportional to the radius. The effect in ordinary stars is very small, though

not undetectable. The main difficulty is that there is no way at all of distinguishing a Doppler red shift from a gravitational red shift. True, the anticipated Einstein effect can be calculated fairly easily. It is most pronounced in the small, very dense white dwarfs. The gravitational red shift should be even greater in the case of neutron and hyperon stars, as yet discovered only by the theoreticians. It was therefore only natural to inquire whether the radio sources were not, perhaps, neutron stars within our Galaxy.

However, the idea, expressed by the American astronomer Burbidge, contradicted one of the observed facts: the prohibited lines in the spectrum, which appear only at low densities. In fact, they are called "prohibited" because they cannot be produced in terrestrial conditions. And as low density is, obviously, quite incompatible with neutron stars, the red shift for prohibited lines should be smaller than for permitted lines. This not being the case, the neutron star hypothesis had to be abandoned.

Thus, radio stars are very remote extragalactic entities. This conclusion immediately made them the most remarkable objects in the universe. Nor is this an exaggeration.

From the distance and apparent stellar magnitude it is possible to compute the total energy emission of radio stars, or quasi-stellar radio sources, quasars, for short, as they are now known. The luminosity of 3C 48 and 3C 273 was found to exceed the luminosity of our Galaxy 50 to 150 times, and that of the brightest elliptical galaxies by ten times and more. Yes, yes, the luminosity of these remarkable objects exceeds the total luminosity of all the billions of stars in the Milky Way.

Quasars emit more energy than any other known object in the universe. Nor do they fade away within a few weeks, like supernovae, but continue to emit their incredible light into space. Already now there are grounds for asserting that the luminosity of 3C 273 is not subject to century variations.

What is the physical nature of these remarkable objects? What is the secret of their incredible luminosity? When astronomers were still arguing about the mysterious lines in quasar spectra, the English astrophysicists Hoyle and Fowler put forward an interesting hypothesis.

Astrophysicists had for long been anticipating the discovery of processes in the universe involving the emission

of vast amounts of energy. Observations of extragalactic radio sources, such as the radio galaxy Cygnus A, demonstrated that radio emission is caused by the magnetic retardation of cosmic electrons. Specific features of the spectrum and the magnitude of the radiation flux in the radio wavelength can be used to estimate the latent energy of cosmic rays and magnetic field. This energy is enormous, being 10 times greater than the potential energy of mutual gravitation of all the stars of our Galaxy.

The idea has been expressed that this vast energy is due to stupendous cosmic catastrophes. For a time the notion of colliding galaxies was a pet theme. But then it was found that radio sources must be associated with some mysterious processes taking place in galactic nuclei.

Ambartsumyan, it will be recalled, drew attention to galactic nuclei, seeing in them the key to many mysteries of the universe. Burbidge expressed the idea that in the conditions prevailing in a galactic nucleus a supernova explosion may spark a chain reaction of explosions, providing the source for this powerful radio emission. The hypothesis is an interesting one, especially as stellar density in galactic nuclei is very high.

Hoyle and Fowler went on to show that a chain reaction is possible only if the exploding stars are very close to each other, in effect touching. But if that is the case then they constitute a single entity, a superstar. In an article on the nature of powerful radio sources, Hoyle and Fowler wrote that, however strange the notion of stellar-type objects with masses 10^8 times that of the sun, the very nature of the question requires an unusual physical situation.

The superstar concept is definitely "mad" enough to be quite in the spirit of the age. On the other hand, however, it is quite traditional. In a sense it is in line with the notion of a hierarchy of systems. It could be recalled that at the end of the 18th century many scholars were convinced that a huge celestial body lay at the centre of the Milky Way. But these are minor considerations. The main thing is that this is a challenge to the classical concepts of Jeans, who had demonstrated convincingly that stars of thousands of times the sun's mass simply cannot exist. And here we have millions of times!

Superstars are unstable formations. They undergo compression, which must liberate vast quantities of gravitatio-

nal energy, making them likely sources of radio emission. It was not long, therefore, before "radio stars" and "superstars" were both identified as "quasars".

The nearest quasar, 3C 273, lies 1,500 million light-years away. The total flux of electromagnetic energy emitted by it amounts to something like 2×10^{46} ergs per sec. This is 33 orders of magnitude more than the energy emitted by the sun, and 100 times more than the total emission of the Galaxy. Fluctuations in the luminosity of 3C 273 (discovered independently by A. S. Sharov and Yu. N. Yefremov in the Soviet Union and H. Schmidt in the United States) provided a clue to its size. The quasar's luminosity was observed to change substantially even within a single week. As the dimensions of a body cannot exceed the product of the velocity of light and the observed period of luminosity fluctuations, the diameter of 3C 273 must be no greater than 2×10^{16} cm, or about one "light-week" (1/52nd of a light-year). The mass of 3C 273 is estimated to be 10^8 solar masses.

GRAVITATIONAL GRAVES

Let us now see how the gravitational energy of compression of a great mass turns into other forms of energy. This is the energy transformation that has enabled men to discover such distant objects as quasars.

There are reasons to believe that quasars are formed from clouds of rarefied gas which contract in their own gravitational fields. If there are no strong turbulent motions in the huge mass of gas it contracts very rapidly. Although compression causes heating, and heating increases pressure, the contraction nevertheless continues and there is nothing that can stop it.

Let us estimate the dimensions to which a gas mass equal to 10^8 suns must contract for the conversion of its gravitational energy into cosmic radiation to ensure a reserve of 10^{60} ergs. To be sure, it is hard to say what the efficiency of gravitation conversion into cosmic rays is, but if we take one per cent we shall evidently not be too far off the mark.

The potential gravitational energy of a mass M of radius R is, approximately,

$$E_{pot} \approx \frac{GM^2}{R}$$

The unknown quantity is R, the others are given as: G=Newton's gravitational constant; $E_{pot}=10^{60}$ ergs; $M=$ $=10^8$ suns$=2\times10^{41}$ grams; the efficiency, we agreed, is 1 per cent.

The result, then, is $R=2\times10^{43}$ cm.

At distances of this order of magnitude the potential energy of gravitation is comparable with the intrinsic energy of matter, which is equal to the mass times the square of the velocity of light. In this case we can no longer apply Newton's gravitational theory, and the effects of relativity theory manifest themselves to the fullest extent.

Hence, the problem is of necessity reduced to the case of a strong gravitational field possessing spherical symmetry.

You will recall that, according to relativity theory, gravity is a manifestation of the curvature of four-dimensional space-time. This means that in the vicinity of massive bodies the geometry of space ceases being Euclidean and time flows differently than at a distance. The rate of flow of time is the slower the closer it is to such a mass.

Suppose a spaceship is dispatched to study this mass. Its crew has orders to send a signal earthwards every second. Years and years later the signals have spanned the distance and the men on earth start receiving them. But what is this? Instead of coming in every second, as agreed, they get rarer and rarer: at first minutes apart, then hours, months, centuries! Yet the astronauts had all the time been sending them out at regular one-second intervals — according to *their* clock.

This short story, which could provide a plot for a science-fiction thriller, can be expressed in simple mathematical terms involving neither integrals nor tensors, using an apparatus no more formidable than a square root. Thus, if a clock far away from the immense gravitational field shows that a time Δt has passed, in the vicinity of the gravitating mass the respective interval will be:

$$\overline{\Delta t} = \sqrt{1 - \frac{2GM}{c^2 r}}\, \Delta t$$

where r is the circumference, divided by 2π, of a circle drawn around the mass through the given point. It should be noted that r is not the radius of this circle, as would seem apparent, for, as mentioned above, Euclidean geometry is no longer valid for the conditions described. But, the closer r approaches the gravitational radius $R_g = \frac{2GM}{c^2}$ the longer the time interval Δt and the slower the course of time. The distance $r = R_g$ is called the Schwarzschild radius.

As the Schwarzschild radius is approached strange things occur not only with clocks. The closer r to R_g the greater the gravity, which in the limit tends to infinity. If a contracting body passes the fatal gravitational radius there is no force in the universe capable of halting its further contraction. The body will collapse irresistibly into itself.

Imagine yourself as an observer watching a star contract to the gravitational radius: you are in for a great disappointment. As it nears the Schwarzschild radius time, as just pointed out, slows down. Therefore, however fast the star contracts, the process will seem interminable to the external observer. Then at one fine moment light from the contracting sphere will not reach him at all. We shall never be able to observe a star that has contracted into something smaller than the gravitational radius. Its dimensions will only asymptotically approach the Schwarzschild radius in an infinite time. Although the star continues to produce radiant energy the gravitational field keeps it from escaping. It continues to live its turbulent nuclear life yet it vanishes from sight. The only mode of interaction between a star that has collapsed in upon itself and the outside world is through gravitational attraction, which is why Zeldovich aptly calls such a star a "gravitational grave".

Calculations show that a collapsing star will disappear from sight and become a gravitational grave about 15 minutes after it has reached the stage at which relativity effects come into play.

A contracting star is no doubt an awesome sight, yet a comparison with quasars makes one wonder: after all, we at least *see* quasars! Far from collapsing into themselves, they abundantly radiate streams of energy into the universe. But this is just the difficulty that has confronted

the theory. The riddle of quasars will not be resolved without an understanding of how the energy of contraction is converted into other forms of energy.

One ingenious suggestion comes from an American scientist who assumes that as a superstar contracts electron-positron annihilation takes place in its hot interior, breeding neutrinos and antineutrinos. The elusive particles easily escape from the giant star trap, which is almost as transparent to them as vacuum, carrying off a substantial portion of the star's mass. The gravitational pull of the nucleus decreases and the pressure which had formerly balanced it now begins to push out the external shell. An explosion takes place in which the incredible energy of 10^{60} ergs is released.

However, Zeldovich came to the conclusion that this scheme is hardly feasible in view of general relativity effects, which it fails to take into account.

A very large mass attains the Schwarzschild radius while its density is still comparatively small. For an object of 10^8 solar masses, for example, the density need not exceed 2 grams per cubic centimetre, or only twice the density of the sun. At a temperature of 0.5×10^9 °K the star's radius will reach the gravitational radius before the predicted mass neutrino exodus takes place. The mass carried off by particles is so negligible that there is no question of the star shedding its external shell.

Zeldovich suggests the following scheme. A collapsed star's only connection with the outside world is through its gravitational field, which is very large in the vicinity of R_g. The invisible monster can therefore be expected to attract surrounding matter, such as remnants of its old shell and plasma flares thrown off in the early stages of its evolution. The shower of matter falling on the star gradually gives rise to energy radiation of an intensity so great that next to it a nuclear reaction would have the appearance of a firecracker.

Academician V. L. Ginzburg has shown that magnetic fields must play an important part on all stages in the life of quasars. We have said that prestellar gas represents a highly ionized plasma. The magnetic field, which was the same as in all interstellar gas before the contraction began, increases to thousands of millions of oersteds at the surface of the contracted star. An idea of the intensity of

this field will be gained when it is recalled that the intensity of our planet's magnetic field is less than one oersted. We are only too well aware of the spectacular macroscopic manifestations of that one oersted. What can be said then of a field thousands of millions of times stronger?

To be sure, at the final stages of contraction the star's magnetic field disappears together with the visible light, the two being of the same electromagnetic nature. But the tremendous amplification of the field as the gravitational grave builds up induces a hydromagnetic state in the surrounding plasma in which particles are accelerated to limiting velocities. They produce the cosmic rays which emit the radio signals we hear. A quasar is a cosmic gravitational accelerator of unimaginable power. No cosmic cataclysms, no collisions of worlds, real or imagined catastrophes can compare with it. A quasar is a unique, outstanding phenomenon. It is not for nothing that scientists are expecting it to answer many of the questions formerly posed to the universe as a whole.

But today we cannot speak with sufficient confidence of the phenomena taking place within the incandescent sphere which it would take a month to circle travelling at the speed of light. Heated arguments are raging around the various hypotheses. The whole arsenal of theoretical physics is being invoked.

It is not surprising, therefore, that the noble "madness" of 20th-century physics has "infected" adjacent sciences. One of the first victims of the "epidemic" was, naturally, astrophysics.

Celebrated Soviet astrophysicists I. S. Shklovsky and N. S. Kardashev have postulated that the energy liberated in gravitational collapse is emitted as gravitational waves, of which we have already spoken. It will be recalled that the gravitational waves of the whole solar system are comparable in power to an ordinary electric bulb. Not that this should prompt hasty conclusions. After all, as we have seen, the earth's magnetic field bears no comparison at all with the stupendous magnetic intensity of quasars. What we are unable to register on the scale of the solar system on the galactic scale becomes a source of phenomena observable a thousand million parsecs away. If in the immense gravitational field to be found at a distance of several Schwarzschild radii from a quasar there is a clot of

matter revolving about the central body, it will radiate gravitational waves of great strength. Zeldovich and Novikov have shown that a body spiraling toward the quasar will approach to a distance of $3R_g$, from where it will plummet to the surface.

Gravitational waves spread out from quasars like an invisible whirlwind, pervading the universe. Their role, however, should not be exaggerated. Their energy is tremendous as compared with all known processes, but on the scale of a quasar it most likely dwindles to insignificance. Novikov tried approaching the riddle of quasars from more general positions. He began by evaluating the density of matter in the metagalaxy: or rather, the "paleodensity" since it is a question of the metagalaxy as it was 10,000 million years ago. We already know that this can be done. More, we can even guess the results of such an estimate. For when we are speaking of the "youth" of the universe, then, remembering the initial superdense state, we can safely claim that the density was great indeed.

The Soviet researcher then went on to make the purely speculative assumption that conditions in the expanding universe may have varied greatly from one place to another. It follows logically that some of the existing matter as represented by scattered nuclei could have fallen behind the general process and escaped the expansion. The ordinary expanding matter went into the formation of galaxies and stars. Much later the "preserved" nuclear matter began to evolve. Today we can see galactic "dinosaurs" obeying the general law long after their time and emerging out of their Schwarzschild radii to take part, at long last, in the general expansion.

The mathematical apparatus of relativity theory allows for such a possibility. Preserved nuclei are gravitational graves, like collapsed stars. Novikov approaches the problem from the other end: some researchers declare that the Schwarzschild radius is a quasar's future; he insists it is its past. From the purely philosophical point of view such an approach is quite legitimate. Evolution follows both ascending and descending lines. When outside matter falls into the gravitational field of an expanding nucleus it encounters matter escaping from the Schwarzschild radius. In the process the colossal energy thanks to which quasars were discovered is released.

Novikov's hypothesis in effect develops Ambartsumyan's cosmological theory of the evolution of superdense prestellar matter.

The unusually intense radio emission of quasars continues to worry scientists. As one young participant in a symposium on the question held in the United States in December 1963 declared, it was a matter of scientists' honour to explain the phenomenon of quasars.

Let us get acquainted with three new theories of the origin of quasars.

Field, a worker of Princeton University, holds that quasars are in fact an early stage in the evolution of ordinary spherical galaxies. Such a galaxy could form from a rarefied hydrogen cloud with a mass of approximately 10^{11} stars. At first the contraction would proceed slowly, then accelerate steadily until the cloud contracts to within a radius of several hundred light-years. Such a sufficiently dense and compact galactic object would already be comparatively stable. But sooner or later the condensation of gas into stars commences in the embryonic spherical galaxy. The process involves the whole cloud, which begins to expand. Of the 50,000 million stars that can form in this early stage most will be of the brightest type. This means that their matter burns out almost simultaneously. Eventually they all become supernovae, a process which takes no more than one million years. And the energy output of all the supernovae is just the magic number 10^{60} ergs.

Each year from 60 to 140 supernovae explode; their statistical fluctuations readily explain the mysterious fluctuations in the luminosity of quasars (the radiation intensity of which may fluctuate within ± 40 per cent). When more supernovae explosions occur the quasar appears brighter, when there are fewer our instruments register a decrease in luminosity.

Alongside this very conservative theory, which could have been espoused by any 19th-century scholar, the theory of New York astrophysicist Hofmann seems absolutely fantastic. Had we not devoted space to negative energies and masses in this book it would have been very difficult to present Hofmann's theory.

It will be recalled that according to Einstein's equations (and Newton's too, for that matter) both positive and negative masses are subject to gravitational attraction. Only,

unlike the laws of electricity, masses of the same sign are drawn together and of opposite sign repel. Proceeding from general relativity, Hofmann assumed that both kinds of masses can radiate gravitational waves. They transmit only positive energy, regardless of the "charge sign" of the mass generating them. From this feature of gravitational waves follows a profound and far from apparent corollary: a particle of positive mass is capable of transmuting into a particle of negative mass. All it has to do for this is emit gravitational waves with a positive energy equivalent to more than its positive mass. Further emission of gravitational waves obviously increases the negative mass.

Hofmann assumes that the conservation laws prevent the recharging of particles of positive mass into particles of negative mass. However, he writes, in the very unusual extreme conditions inside quasars the laws of symmetry may break down. This could be caused by extremely dense packing of the particles and/or very high gravitation.

For example, superdense packing may result in such tremendous nuclear forces that particles of positive mass will begin to emit gravitational waves. Intense gravitational radiation could in itself be a symmetry violator enabling particles of positive mass to recharge into negative. In the process stupendous energy would be emitted, positive, of course. The very enormity of the energy output of quasar makes it necessary to forego conventional explanations, and it is precisely for this reason that the idea of negative mass deserves serious consideration, concludes Hofmann who, incidentally, once worked alongside Einstein and Infeld.

A most unusual theory was put forward by Terrell, a worker of the Los Alamos laboratory. If the history of a quasar is regarded as a tangled criminal case, Terrell can be said to have approached it in the style of a Sherlock Holmes or Hercule Poirot. His reasoning is unexpected and nontraditional.

In the first place, he disagrees with the views of all other experts dealing with quasars. As we have seen, all theories, however much they may contradict each other, share one thing in common: they regard quasars as remote extragalactic bodies. This is just what Terrell rebels against. He considers them to be closer to us than other galaxies, somewhere between the Milky Way and the Andromeda ne-

bula. He sees proof of this contention in the fact that quasars display fluctuations in radiation intensity of a frequency possible only in comparatively small bodies. In Terrell's view they can hardly be bigger than the solar system. But if that is the case then the velocity of quasars relative to us and neighbouring galaxies must be extremely great. And this in turn can only be the consequence of a gravitational collapse once experienced by the Milky Way and neighbouring systems.

WITNESSES OF THE BIRTH OF THE UNIVERSE

However ingenious and beautiful Terrell's theory may seem, it is the first to collapse under the burden of facts. Every day we obtain new proof that quasars are in fact extremely remote objects. In 1964, the farthest quasar was 3C 147. Its velocity is 40 per cent the speed of light, which corresponds to a distance of several thousand million light-years. Only a few months passed, and object 3C 9 was found to have a recession velocity of 240,000 km per sec, or 80 per cent the speed of light. Maarten Schmidt estimates that the light now recorded from 3C 9 left it only two or three thousand million years after the universe was born; the universe is estimated to be ten to fifteen thousand million years old.

The American Allan R. Sandage used the 200 inch telescope to identify a new class of objects resembling quasars which do not emit radio waves. Originally Sandage could not decide what to call the newcomers. Eventually he named them blue stellar objects (BSO).

Incidentally, the blue luminaries were known to the astronomers long before, but no one had suspected them to be so far away, and they were taken for ordinary blue stars of the kind populating the fringes of the Milky Way. It turned out from a study of their spectra that the BSO's have red shifts comparable to those seen in the spectra of quasars.

Sandage and Schmidt measured the velocities of several blue stellar objects and found that BSO No. 1, for example, is receding at 200,000 km per sec, a velocity that is second only to that of 3C 9.

The study of BSO's holds promise of many surprises. What makes them so important is that they appear to be

about 500 times more plentiful than quasars. Sandage estimates that there are more than 100,000 BSO's down to the 19th apparent magnitude. They are so numerous and reach so far into space that they could be used to determine the effects of space curvature and the slowing down of the expansion of the universe. In other words, they involve some of the most fundamental problems of science. Some researchers hold that the expansion of our presumably closed universe is gradually slowing down, which would mean that the time will come when the remotest galaxies will reverse their motion and the universe will begin to contract.

This may perhaps be verified after a careful study of thousands of blue stellar objects. The hunt for the remotest metagalactic targets is now in full swing. Scientists are feverishly seeking "witnesses" of the explosion of the superdense universe, the "big bang" as it has been called. Experiments carried out at the Bell Telephone Laboratories may have detected the first radiation to become disengaged from matter after the "big bang". The evidence for such radiation was found during a series of precision measurements made at a wavelength of 7.3 centimetres. The experimenters, Arno A. Penzias and Robert W. Wilson, set themselves the objective of accounting for all known sources of radio noise wherever they might be, in the depths of the cosmos or the interior of the earth. The investigations, carried out with a large horn-reflector antenna used for communication-satellite systems, revealed an unexplained residuum of noise. As is so often the case, the discovery owed itself to pure chance. It had not been expected or looked forward to, as the purpose of the study had been entirely different. When they encountered the unexplained phenomenon the researchers began to seek a natural explanation for it. In a recently published article they learned that an all-pervasive radiation extending to the 7.3 cm wavelength had been predicted in a new hypothesis proposed by workers of Princeton University. The authors of the article had calculated that if the universe had originated with a big bang, it should have reached a temperature of 10,000 million degrees on the Kelvin scale or more. At such high temperatures radiation would be absorbed almost as fast as it was emitted. Finally, after the temperature had dropped to 100 million degrees, radiation would be "decoupled" from matter and set free to begin a journey through the universe that still continues.

The Princeton workers had predicted that this primordial radiation would have consisted chiefly of gamma quanta and that its wavelength would have been shifted into the centimetre range by its long journey through an expanding universe. The radiation as it were cooled in the same manner as a hot jet of gas cools when it passes from a jet engine into the expanding nozzle.

The Princeton workers were just preparing to seek to confirm their hypothesis experimentally when news of the work at the Bell Laboratories arrived. Although it is too early to draw any final conclusions and the results of new experiments must be awaited, it is apparent that the radiation detected by Penzias and Wilson is really primordial.

Before ending with this brief digression from the story of quasars, let us mentally go back to the pages where we spoke of the birth of the universe. The authors of those interesting hypotheses had most likely never expected the experimental verification of them to be so close. Now suddenly the first experiments in this direction have been carried out, and not by scientists but by radio engineers concerned with the orientation of satellites with respect to stationary radio targets.

The quests of individuals may be fortuitous, but the common road of science dialectically brings them together into manifestations of natural laws. That is why in our time there are no isolated scientific strongholds. All branches of science are interdependent and success in one field can only be a consequence of success in others, sometimes even very remote.

Quasars are in a way linked with a sensational piece of news which set first Moscow and then the whole world agog. For me it all happened when a well-known newspaper woman called me up.

"Have you heard the big news?" she said breathlessly, her voice quivering with the excitement of discovery.

"No."

"No?"

"No."

"Signals from an extraterrestrial civilization have been received!"

"What?!"

"Hurry to the Shternberg Astronomical Institute. A news

conference has been called there. All the foreign correspondents have rushed to it."

You may remember the event. The news of the Soviet astronomer's exciting discovery was printed in all the papers. Only where our charming representative of the press had used a "!" her colleagues had preferred a "?" and even "??". Which is understandable. It is one thing to shout into the telephone, "Signals from an extraterrestrial civilization have been received!" and quite another to print the report in a newspaper. Especially as the news conference at the Astronomical Institute had a sobering effect on some overzealous so that the headlines on the following day were variants of "Signals from Extraterrestrial Civilization? Don't Jump at Conclusions, Scientists Say."

The "signals from an extraterrestrial civilization" were registered by a radio telescope. It was not an accidental discovery since the search for variable radio sources had been going on for quite some time. Interest in these investigations was prompted by theoretical considerations and a number of observed phenomena, notably the variable luminosity of quasars 3C 273 and 3C 48 in optical light. The theoretical considerations have been mentioned here in connection with the question of radio emission on the 21 cm wavelength. Furthermore, comparatively recently N. S. Kardashev voiced the interesting idea that highly developed civilizations could beam radio signals of exceptional intensity into space. In his view artificial radio sources would most likely be characterized by a radio spectrum with the power peak in the centimetre bandwidth and small angular dimensions.

Two extremely interesting cosmic radio emitters discovered by American astronomers are known by the names STA 21 and STA 102. The interesting thing about them is that the power peaks in their spectra fall just on the centimetre region and their angular dimensions are too small to be measured.

A team of Soviet astronomers under G. B. Sholomitsky found that the radio emission of STA 102 is of a variable character. A series of measurements confirmed that the radio flux from STA 21 is constant while the flux from STA 102 varies periodically with time.

It would seem that STA 102 meets all the requirements of Kardashev's hypothesis and can be regarded as an arti-

ficial source. However, such conclusions should be drawn only as a final resort, when no other explanations fit the phenomenon. Otherwise science will cease to be a means of cognition. It will be swamped by Martian canals, cosmic visitors, abdominable snowmen and Tungusska spaceships. All of these are no doubt exciting problems, but they have no place in discussing scientific findings. This is not to say that science should reject fantasy out of hand. But the "fantastic component" in modern natural science is adequately represented by "mad" ideas. The traditional ideas of fantasy are too superficial, too unimaginative for science.

Thus ended the sensation which should never have been in connection with the very interesting and as yet mysterious phenomenon discovered in Moscow.

Astronomers are looking forward to the results of observations of a weak star of 17.5 magnitude identified with the radio source STA 102. Its spectrum will tell us its distance. If STA 102 is found to lie outside of our Galaxy scientists will have their hands full with classifying this radio emitter.

As for extraterrestrial civilizations, the reader is advized to look up I. S. Shklovsky's book, *Universe, Life, Intelligence*, which is available in English translation. My own conclusion after reading it is that our chances of meeting alien intelligence are exceedingly remote.

GALACTIC EXPLOSIONS

In recent years astrophysicists have been speaking increasingly of titanic explosions taking place in the central regions of certain galaxies. The energies released in these explosions could account for the highest observed cosmic ray energies. This hypothesis is strongly supported by observations of a neighbouring elliptical galaxy which indicate that the galaxy was the scene of such an explosion, as well as by evidence provided by radio astronomy.

Since the discovery of Cygnus A, mentioned above, radio astronomers have detected and mapped more than 3,000 discrete radio sources. Their number is multiplying rapidly and, specialists estimate, will probably pass 100,000 when comprehensive surveys now in progress are completed.

Since Rudolph Minkowski and Walter Baade showed that the discrete radio sources Cygnus A and Centaurus A coin-

cide with giant galaxies more than 100 radio sources have been identified with visible galaxies, and it is likely that most of the other sources are associated with galaxies or quasars which are either too distant to be seen or have a luminosity beyond the limit of the 200 inch telescope.

In 1950, the Swedish astrophysicists Hannes Alfven and N. Herlofson offered the first physical explanation of the origin of galactic radio emission, subsequently developed by the Soviet astrophysicist I. S. Shklovsky. We have already mentioned that radio waves are generated by the interaction of relativistic electrons and a magnetic field. As an electron gyrates around a line of force in a magnetic field it accelerates and emits energy in the form of electromagnetic quanta. This radiation is sometimes called synchrotron radiation, since it is identical with the radiation produced in manmade synchrotrons. The frequency of synchrotron radiation depends on the energy of the gyrating particles and on the strength of the magnetic field. Radio waves are produced when the electron energies lie between one and 25 GeV and the magnetic field has a strength of about a millionth of a gauss. These specifications are amply met by radio galaxies. In fact electron energies of 25 GeV may represent only the lowest end of the scale. For example,M 87 is an intense radio galaxy in which electrons gyrate at velocities unattainable in any manmade accelerator and their energies appear to be at least 10,000 GeV.

Such superfast particles must eventually escape the magnetic fields of the radio galaxies and fly off into space. These particles, together with others generated by similar explosions in our own Galaxy, could account for the flux of cosmic radiation that enters the terrestrial atmosphere.

Considering the density of radio galaxies in space, their estimated lifetimes and their total output of energy (and also taking into account the production of fast particles in our own stellar system), one can predict both the intensity of the observed cosmic radiation and the energy of its fastest particles.

More and more data appeared to confirm the hypothesis that galactic explosions are a source of synchrotron radiation and subsequent investigations added detail to the model without affecting its physical basis.

In 1953, workers of the Jodrell Bank radio observatory discovered that Cygnus A could be resolved into two distinct

radio-emitting regions separated by a distance of about 100,000 light-years. Today it is known that this phenomenon, which has been called radio doubling, is probably the rule rather than the exception among radio galaxies. Presumably the twin radio regions represent two jets of high-energy particles ejected by the parent galaxy in an explosion millions of years ago. Conserving angular momentum, the jets would move in opposite directions. They would carry part of the galaxy's magnetic field with them and synchrotron radiation would be produced all along them, but it would be most concentrated at the ends, where the lines of force of the magnetic field would be most tightly compressed; in effect, two discrete spots of radio emission would be observed.

In spite of persuasive evidence, the exploding galaxy hypothesis seemed hard to accept finally in the absence of optical support. It was felt that the most stupendous of cataclysms of the universe had to be visibly seen.

In 1961, workers of the U.S. National Radio Astronomy Observatory in Green Bank, W. Va., were surveying a group of visible galaxies centred on the giant spiral galaxy M 81 in an attempt to locate a weak radio source designated 3C 231. This source had previously been identified with M 81 itself, but more accurate measurements showed that it actually coincided with the peculiar galaxy M 82, a smaller neighbour of M 81, and markedly different. Older photographs of M 82 made in 1910 showed that this galaxy could not be resolved into individual stars, although at its distance normal stars should have been visible within the galaxy. The old plates showed extensive dust lanes across the spindle-shaped image of the galaxy, with a faint filamentary structure around the galactic "poles".

In 1961-1963, the Americans C. R. Lynds and Sandage made a new series of photographs of M 82 using the 200 inch telescope. A special interference filter that admitted only red light with a wavelength corresponding to the so-called hydrogen-alpha line was used. And the new plates showed M 82 in an entirely new aspect. What had appeared on the old plates as inconspicuous filamentary whisps now appeared as vast and intricate hydrogen structures extending some 14,000 light-years above and below the plane of the galaxy. Soon it was found that the filamentary structure on one side of the galactic disk was approaching the earth, whereas

the structure on the other side was receding. This observation could be interpreted as evidence that the galaxy is either exploding or imploding. A more thorough analysis revealed that the filaments on the south side of the galactic disk were approaching the earth and that the filaments on the north side were receding. If the north edge of the galactic disk were nearer the earth spectral tilting would indicate that the galaxy was in the process of expansion. If the south edge were nearer the galaxy would be collapsing. The problem could be resolved only by direct measurement.

Back in the 1920s, V. M. Slipher had pointed out that most of the dust in galaxies is confined to a thin sheet coincident with the central plane of the galaxy. Hence for galaxies seen edge on, the near edge of the galaxy will be distinguished by dark dust lanes silhouetted against the bright nuclear bulge, whereas the dust lanes on the far edge will be much less conspicuous, since there is no background light for these lanes to obscure. The criterion, it will be noted, is both clear and simple and it decided the fate of M 82. The north side was found to be closer to us than the southern. It follows that the material in the filaments must be moving outward from the centre of the galaxy.

Further spectral measurements provided even more conclusive evidence when it was found that the greater the distance from the centre of the galaxy the more the spectral lines appeared to be inclined. The obvious conclusion was that the velocity of expansion of the filaments on each side of the galactic disk must increase linearly with their distance from the centre. When the tilt of the galaxy along the line of sight was calculated, it was found that the velocity of the matter at the ends of the filaments reaches 1,000 kilometres per second.

The direct relation of velocity to distance in the filaments can be taken to mean that all the matter in them must have been back in the nucleus of M 82 at a given time in the past. This is strong evidence for regarding the filaments as the residue of a single vast explosion in the nucleus of the galaxy. Calculations indicate that the explosion occurred some 1.5 million years ago. In dealing with the past of galactic objects one must always make adjustments for distance. Since M 82 is roughly 10 million light-years away, what we are seeing are the effects of a catastrophe that took

place 11.5 million years ago. We can only guess what M 82 actually is like today, if it is there at all.

The amount of matter moving outward from the centre of M 82 can be estimated from the strength of the hydrogen-alpha emission line in the spectrum of the filaments. Calculations carried out by Sandage showed that about 10^{63} low-energy protons and electrons must be present in the filaments. This is equivalent to roughly five million times the mass of the sun. The energy needed to set this huge mass of matter in motion is about 2×10^{55} ergs.

Specialists regard M 82 as a typical radio galaxy, and although it does not exhibit two separate regions of radio emission, these may perhaps develop later in its history. In other words, the filaments have not yet evolved into jets with "electron bombs" on the tips. The filaments of M 82 have counterparts in many other radio galaxies. Jets of high-energy gas have been observed in other radio emitters, from galaxies of the type of M 82 to quasars 3C 48 and 3C 273. A particular interesting example of the phenomenon can be seen in the spiral galaxy NGC 4651, which has been identified with the radio source 3C 275.1. In this galaxy two jets extend from opposite sides of a spiral arm to distances of about 50,000 light-years!

Once again on the order of the day is the problem of energies. The synchrotron model enables us to calculate the total energy required to produce a galactic explosion; in the case of M 82 this input of energy amounts to about 10^{57} or 10^{58} ergs. Radio sources like Cygnus A, Hercules A and Hydra A undoubtedly originated in even more stupendous explosions the energy input for which is perhaps as much as 10^{62} ergs. Thus we come back again to the problems posed when we were discussing quasars. We find the same energies, the same reasoning, the same hypotheses. Who knows, perhaps a quasar is but the initial stage in the evolution of a radio galaxy. Or maybe they are galactic nuclei stripped of their "shells"?

Answers to these and many other questions of interest may be forthcoming in the next few years. Explosions of quasars and galactic nuclei dwarf all known physical processes. Their discovery will undoubtedly enrich science with new facts and new ideas.

Meanwhile we can regard metagalactic explosions as a probable source of cosmic radiation.

PART SIX

The Universe And Infinity

A LONG DIGRESSION ON THE SUBJECT OF TIME-REVERSAL

We have had a chance to get acquainted with quite a few abstract notions, but here is one which probably beats them all: the idea that, in principle, material objects can move in a reversed time-flow from the future to the past (from our own point of view, of course). The "madness" of modern physics rarely lies at the surface. Before the full meaning of a scientific idea can be fully understood one must enter a strange world of conventions peculiar to it. If all the books in your library were written in different languages you would have to learn a new language every time you took one from a shelf. To be sure, science has one language, mathematics, but, firstly, in this narrative there will be hardly any mathematical symbols, and, secondly, every fundamental idea has certain conventions peculiar to it alone.

Thus, our task is to master the principles of four-dimensional geography. When we describe an interaction of particles we must know not only the time and place of the event but also its space-time path. We all know what a geographic map is like. Usually the southnorth direction is from the bottom edge to the top and the east-west direction is from right to left. A map is convenient for representing a two-dimensional spatial path. Here is the winding road followed by a car travelling from Moscow to Tula or the straight line of a plane flying to Leningrad. If the map is on a sufficiently large scale a small circle can even show the path of a proton in the Dubna synchrotron. Every moving object can be traced on a map. But a map is no more than a vertical projection, and it can't tell us at what height the airplane flew. For this a three-dimensional model is needed. And

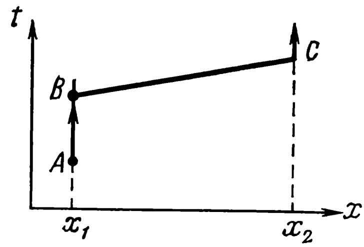
even this is not enough for the full history of objects, which move through time as well as space. The model does not tell us when the car passed through different places or when the airplane rumbled overhead. This requires a four-dimensional model, though no one knows what it may look like. This is only natural, as we live in a world of three dimensions and it is quite impossible for us to imagine what four-dimensional space is like. In speaking of the geometry of the universe, however, we introduced an analogue in which we tried to look at ourselves through the eyes of two-dimensional inhabitants of the surface of an expanding balloon. So now all we have to do is continue our thought experiments.

If we cut the outlines of both hands from a sheet of paper we will have two five-fingered silhouettes virtually identical in all respects save that they can be superimposed only if one of them is turned over. This is to say that they are symmetrically opposite mirror reflections of each other. Recalling our story of the problems of parity, we can say that what we do in superimposing them is performing a mirror inversion. How is this done? Let us try and analyse the process. We lift the silhouette out of the plane it is in, turn it over and return it to the plane. This is the same as saying that we removed the silhouette from its two-dimensional world, turned it over in the three-dimensional world and then put it back in the universe of two coordinates. From the point of view of the inhabitants of that universe we have performed an incomprehensible miracle. But now let us try and perform a similar miracle with casts of the hands. Here we are bound to fail. There is no way of superimposing the casts, because they are three-dimensional. To "turn" one over it has to be taken out into the four-dimensional world. And the fourth dimension is outside of space just as the third is outside a plane.

In the imaginary world of four dimensions we could produce mirror images by simply flipping over objects, put a left glove on the right hand, get a view along the fourth perpendicular of all of a series of nested dolls, place butterflies in inflated balloons without piercing the rubber and even turn a balloon inside out without letting out the air.

Of course, all these fantastic possibilities exist only as purely geometric abstractions. But the theory of multidimensional spaces has an important part not only in mathe-

matics but in physics as well. Many problems connected with the behaviour of molecules, atoms and elementary particles can be solved only with the help of multidimensional geometry. But this is not what interests us at present. To the miracles that can be performed in four-dimensional space we shall add one by constructing the four-dimensional map or model mentioned before.

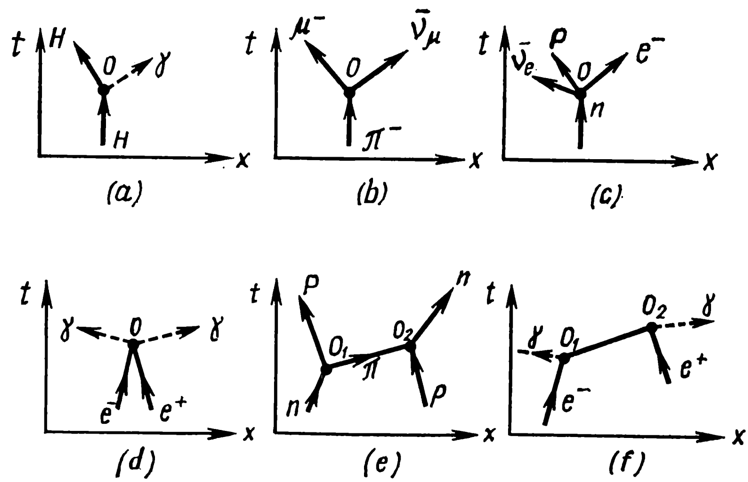


Let us try and represent the history of an airplane's flight in space and time. Suppose the plane is flying to the east. In that case we can dispense of the south-north coordinate, substituting the time coordinate, t. The x axis gives us distance.

A spatio-temporal map has no point which would correspond to rest. Even the airfield (x_1) from which the plane took off does not remain at rest, moving as it does through time. Its position on the x axis remains unchanged, its motion through time being recorded on the t axis, leaving a vertical track which is called a "world line". The world lines of airdromes x_1 and x_2 are represented by the broken-line verticals on the diagram. As long as the airplane is parked on the airdrome it also moves only through time, i.e., vertically up (line AB). When it takes off the plane is displaced in time and space (BC). When it lands at x_2 it stops moving through space and its world line once again becomes a vertical. Spatio-temporal diagrams can be used to describe motions only in a straight line. But as a rule even this is adequate to offer a graphic representation of interactions of elementary particles.

The six diagrams below are the world lines of some elementary processes. Fig. (a) represents the emission of a photon by a hydrogen atom. The vertical world line indicates that the atom is motionless in space. The point O

is what is known in relativity theory as an "event" at a specified point of space and time. On ejecting the photon to the right the atom comes into motion. Its speed is less than that of the photon, which is shown by the smaller inclination of its world line from the vertical. The photon's world line approaches the horizontal, but, like any other, it can



never be quite horizontal as this would denote instantaneous motion. The world lines of photons and neutrinos come closest to the horizontal as they travel at the highest speed, the velocity of light.

Fig. (b) represents a pion decaying into a muon and an antineutrino. At point O it ceases to exist and its world line terminates. At that very place and moment the decay products appear and scatter at different angles at speeds proportional to the angles of inclination.

Fig. (c) represents a neutron decay event, Fig. (d) the annihilation of an electron-positron pair with the emission of two gamma quanta, and Fig. (e) a process of pion exchange between two nucleons.

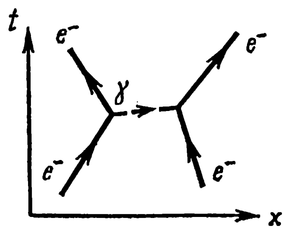
It should be borne in mind that the elementary events taking place at the points O may in fact represent complex sequences of events. But they occur in such small spatiotemporal domains that we take the sequence of events as one event. In fact the annihilation of an electron-positron

pair does not take place as shown in Fig. (d), and the photons are emitted not from one point but from different points, as shown in Fig. (f). However, the spatio-temporal separation between points O_1 and O_2 is so small that they merge into one. In general, it should be understood that particle annihilation and creation events only appear to be instantaneous. In fact they may be an end result of a series of events taking place in very small domains of space and time.

Diagrams of the kind we have just got acquainted with are known as Feynman diagrams, after the 1965 Nobel Prize winner in physics who showed that they correspond exactly to the mathematical expression of the field theory of electrons and photons.

Let us examine the "scattering" process of two electrons from the point of view of the latest theories. Two electrons draw closer together. Then the left particle emits a photon and its velocity changes. The right electron absorbs the photon, which also changes its velocity. The change in motion means that the particles interact, or at least influence one another. The interaction is apparently effected by means of photon exchange. To be absolutely precise, however, the initial interaction is not between electrons but between each electron and a photon.

The second electron has no direct information about the first. The traditional concept of action at a distance linking two bodies becomes meaningless. It is replaced by the concept of local interaction. In our case, each electron interacts with a photon locally, at the point it is in at the moment.

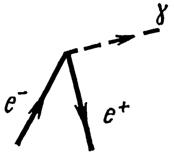


The Feynman diagrams are not as simple as they may appear at first glance. They have a much deeper meaning. Take, for instance, the points at which photon emission or absorption occurs. Regarding the solid lines as the world

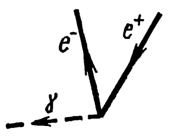
lines of the respective electrons, we find that the fundamental emission and absorption processes are accompanied by a change in the states of motion. But it is possible to give the diagram an entirely different interpretation. For we can regard the apex as a point at which the world line of one electron terminates and the world line of another begins. In this case the apex symbolizes what is literally a cataclysm. This is no longer a change in the state of an individual electron. What happens is the demise of one electron and the birth of a new one. Insofar as all electrons are identical, we have no way of distinguishing one from the other. One may ask if we are not merely trying to be clever when we say that the deflected electron is a new particle. The answer is no. More, this concept is more in line with the mathematical apparatus of the theory of fundamental interactions.

Now suppose we change the directions of the arrows on the world lines. From the purely formal aspect this enables us to distinguish particles from antiparticles: one direction denotes particles, the other, antiparticles.

In this case Fig. (a) below represents the annihilation of an electron-positron pair, while Fig. (b) is the creation of the same pair.



(a)



(b)

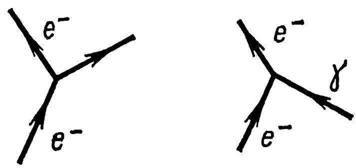
These diagrams are as it were inverted with respect to the familiar diagrams of events in which electrons take part.

It derives from this that the rotation of the fundamental electron-photon apex in space-time will describe all feasible fundamental interactions between electrons, positrons and photons. This, in turn, offers a simple generalized idea of what constitutes the bedrock of all electromagnetic processes.

Investigating these diagrams, Feynman found that the change of the arrow was something much more important

than an ingenious device. Field theory states that the birth of a positron is equivalent to the death of an electron. We know this from our discourse on the Dirac ocean. One can go one step further and say that the mathematical description of a positron field propagating in time is identical to the description of an electron field moving in the reverse temporal direction.

We are assaulting the very fundamentals of common sense when we declare that elementary particles can move not only



from past to future but from future to past as well. This, however, is no cause to jump at conclusions. To be sure, a positron can be described as an electron moving in the opposite direction of time. However, and this should be clearly realized, there is no binding necessity to use this description, and we are fully entitled to offering one in which the positron behaves most trivially and its world line points in the same direction as yours or mine. It is simply that the concept of time reversal clarifies the picture of elementary events and offers a beautiful explanation of the existence of antimatter.

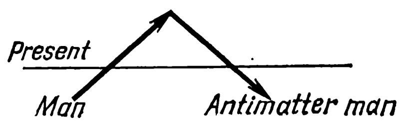
Let us try to apply Feynman's time-reversal device to man. All this is, of course, sheer fantasy—known in science-fiction as the time machine. Thus, we are out to prove that we are moving with time from past to future and are denied the priveleges enjoyed by elementary particles. In other words, we must prove the impossibility of a time machine of any kind. It could be argued that in principle man could have possessed the freedom of sailing the waves of time that particles enjoy. But for some reason or other man is made of particles, not antiparticles, and particles travel in the direction of the future.

We approach the question in principle, and are therefore entitled to inquire in full seriousness whether we cannot, like the electron, reverse our motion through time. The answer is unequivocal: anyone preparing to embark on the vo-

yage would already be knowing of it somewhere in the future. We know what is going on around us at the **present moment,** and the world line which is later to be reversed in time must again pass through the present, that is, through this **same moment.**

The present is a horizontal line. If a man's world line were reversed at that very instant he would have to meet his opposite from the future, a man made up of antiparticles. All this sounds highly fantastic, of course. But only because we are dealing with men, not elementary particles. When we spoke of particles we were not overly shaken by the Feynman diagrams.

Relativity theory distinguishes no preferential direction of time. The apparent one-way flow of time is due to the fact that our world is made up of particles, with antiparticles occurring exceedingly rarely in it. It is only our memory which tells us the direction in which time is flowing, and particles have no such property.



In an article published in the Proceedings of the Royal Society, J. Narlikar analyses two models of the universe. He shows that in one case neutrinos can be displaced in time. Our ideas of the causative sequence of natural events, he writes, may be due to the fact that the universe is continuously expanding since the moment it originated. The existence of a reference point sets the direction of time solely from past to future. As neutrinos interact extremely weakly with other particles and fields, it follows from theory that they can serve as sensitive indicators of the validity of this proposition.

Narlikar suggests an experiment with a neutrino emitter and a receiver capable of registering the particles. If the receiver registers neutrinos only after their appearance in the emitter the experiment will testify in favour of the evolutionary theory of the origin of the universe starting from some initial moment of time. If the receiver detects neutrinos before they appear in the emitter it will be an indica-

tion in favour of an eternal, stable universe. In such a universe neutrinos can be transported into the past. True, the author does not explain how his experiment should be carried out in practice.

INFINITY AND SPATIO-TEMPORAL TWIST

In the general philosophical understanding of infinity we have not advanced far from the ancients. Aristotle's statement that "the investigation of the infinite is difficult as many impossible corollaries derive from both its recognition and its negation" holds true to this day. To be sure the distance from Zeno's celebrated paradoxes to contemporary mathematical constructions is as great as from Hero's steam whirligig to an atomic reactor. Although the age-old argument has long since gone beyond the confines of mathematics its essence has not changed. As Hilbert wrote, it has become a point of honour of human intelligence to determine the essence of infinity.

Practical infinity, logically the simplest type of infinity, was a subject of inquiry for the sages of ancient Judea. Practical infinity is in effect some very large (or very small) number. The criterion of "sufficiently" large (or small) depends completely on the specific problem. Thus, to a nuclear scientist 10 centimetres may be as good as infinite, an astronomer may say the same of millions of light-years, while to a cosmologist both distances are infinitely small. As such, the nuclear scientist's 10 centimetres and astronomer's 10^{24} centimetres are common finite numbers. In their "pure state" they convey nothing at all about infinity. The same as any other large or small quantities. Take, for example, the numbers that give the probability of highly improbable events, such as "Jeans' miracle" of water freezing inside a hot stove. The probability of such an event is as negligible as the probability of a man sitting for the first time in front of a chess board winning from the world champion—a probability computed by the English mathematician Littlewood to be one in 10^{122}. This number is more forbidding than the declaration, "no chance at all". But it is finite. Practical infinity is no more than going beyond a certain limit which may change arbitrarily from one problem to another.

Infinity as endlessness requires a higher level of abstraction. This type of infinity constitutes the basis of mathematical analysis. It took men two thousand years to advance from the practical infinity of Archimedes and Democritus to the infinity of Leibniz and Newton. Right was G. Naan, when he said that these twenty centuries should serve as a warning to those of our contemporaries who so precipitously undertake to prove the "ultimate" solution of the problem of infinity and incidentally "prove" the infinity of the universe with the help of philosophical categories.

When a variable tends to infinity it becomes not simply bigger than some "sufficiently large" value but bigger than any value, however large.

When a variable tends to a finite limit the difference between that limit and the variable becomes smaller than any other value, however small, that is, it passes every boundary in approaching the limiting value. All this is common knowledge to any first-year college student who has begun to tackle higher mathematics. Hegel was justified in calling mathematical infinity (infinity as endlessness) "negative", "foolish", "bad". First people set themselves a boundary, then overstep it, and so on, *ad infinitum*, he wrote.

In Hegel's time mathematical infinity was regarded as the highest type of infinity. In fact, no other types were known. Naturally, therefore, the concept of infinity of space was used merely to characterize its endlessness. To Hegel, as to Engels, spatial infinity was an example of "bad" infinity. Hegel held that true infinity should be not simply a rejection of finality but something "positive and extant", "a relation of measure and laws" which human intelligence discovers in nature.

But it is impossible simply to invent a "true", i.e., higher, infinity. Moreover this is a mathematical, not a philosophical problem. That is why infinity first manifested itself as a "relation of measure and law" in Riemann's metric geometry. Just as infinity characterizing something "positive and extant" emerged as a "corollary" of the Georg Cantor's infinite set theory. Both discoveries were truly revolutionary turning points in the evolution of mathematics and human thinking in general.

Riemann's **metric infinity** introduced an entirely new quality. Suffice it to recall that in curved space, unlike flat Euclidean space, infinity and endlessness are not neces-

sarily the same thing. Curved space can be finite and at the same time endless.

The road from metric to topological properties is quite natural. The topological properties of space are the most stable. Space can deform indefinitely (without violating its continuity) and its topological properties will not change. In this sense topological infinity is more general than metric infinity. For, generally speaking, topology is more stable with respect to deformation than metric.

The principal topological characteristic of space is its connectivity. We spoke of this before in setting forth Ivanter's theory of the mass spectra of elementary particles. If space is simply connected its metric infinity coincides with topological infinity. But the latest scientific data show that real physical space is topologically multiply connected. In consequence, the eternal problem of the finality or infinity of space-time, far from being resolved, becomes more complex than ever. Even from the purely mathematical aspect a topological classification of possible three-dimensional spaces (to say nothing of Einsteinean four-dimensional space-time) is at present an unsolvable problem.

This brief introduction was necessary for an understanding of the essence of the most general of the known types of infinity. We are speaking of set-theoretical infinity. Set theory was enunciated with the specific purpose of overcoming the difficulties inherent in mathematical infinity. It was to become a safeguard against what was aptly called **horror infinity.** And set theory justified the hopes of its creators, only in the process of resolving existing difficulties it gave rise to others. Such is the dialectics of development.

Set theory offered the hope of some day elaborating a positive definition of infinity which would not negate the finite, as Hegel had hoped. In such an infinity Euclid's axiom that the whole is always greater than its part would be inapplicable. We would have to reject many other customary axioms based on common sense.

It should not be thought, however, that new mathematical theories only topple foundations and demand the rejection of age-old truths. Common sense always finds a way out and builds bridges from the new to the old in an attempt to preserve human experience, gained at such high cost. Some theoreticians, for example, hold that in principle infinity cannot be proved, cannot be refuted, and cannot be

deduced. If this is the case then even our most radical concepts of infinity must ultimately rest on some axiom of infinity. It is a vicious circle with no apparent way out. (It would be naive to hope to have this problem resolved once and for all. Ultimate proofs and complete teachings valid for all times evidently do not exist.)

The best theory is not that which removes all contradictions (there are no such theories) but that which most comprehensively reveals their nature.

Since time immemorial men had been sure they inhabited an unbounded flat space and drifted through an absolutely independent world time which flows equally everywhere.

The special theory of relativity showed that we live in space-time which separates differently into space and time depending on the observer. Such a universe has a great variety of times.

The general theory of relativity shattered our illusions of flat space. It condescendingly alowed us to regard space of relatively low density as flat. But in domains of high densities, where space curvature is continuous and positive, endless space becomes finite and closes into a ring sometimes called Einstein's cylindrical world. In such a universe curvature does not change with time, but we have longsince discovered that the metagalaxy is expanding and the curvature changes with time. This is the changing world we are fated to live in.

The general theory of relativity provides for even more complex cosmological models in which time is curved and even closed in on itself. There are other exotic universes of the so-called semi-closed model in which only a portion of space is finite.

On the whole, we are gradually growing accustomed to the fact that the metric, that is, measurable, properties of space or time can be sufficiently "mad".

The desire for some semblance of stability is what mainly prompted expectations of seeing at least topological properties relatively simple. It was foolish, of course, to expect that space would be constructed as we wanted to see it. Simply nature has so far never demonstrated to man any phenomena which could completely deny him what is, after all, a pardonable hope.

As mentioned above, topological, the most stable, properties of space include dimensionality (number of dimen-

sions), connectivity (i.e., in the most general case, the inherent property of space to be made up of one or several portions), and orientability. We are used to living in a three-dimensional, simply connected and orientable world, or if we speak of space-time, then our world is four-dimensional, or more correctly it has 3+1 dimensions. But we have no way of even imagining what, say, a (2+2)-dimensional space, divided into two-dimensional space and two-dimensional time, may look like.

Let us consider Einstein's cylindrical world. Only prior to curling a strip (the flat world) into a ring (the cylindrical world) we shall give it a half-twist. The result is a Möbius strip, something without which, along with the "Looking-Glass World", not a single popular exposition of relativity gets along. A Möbius strip is the simplest example of a one-sided surface or, in other words, a nonorientable space. The twist completely changes many topological properties of the surface. Where an ordinary ring, like any other object about us, has two sides, inside and outside, the twisted ring has only one. We can paint it all over in one colour with a single stroke of a brush without ever going over the edge. Try and do such a thing with an ordinary ring!

A two-sided surface can be separated into two parts by a closed contour or cut in two along that contour. Cutting along the contour in nonorientable Möbius space yields not two separate cylinders as one might expect but one of double diameter and with a double twist. A world in which space-time is analogous to a one-sided ring is truly remarkable. If we travelled around that world, returning to the point of departure, we would have to conclude that time had been moving in the reverse direction. This is hard to visualize as the so-called spatio-temporal framework does not contain the arrows symbolizing the direction of time from past to present. In our simple experiment with the twisted ring we see that the orientation of the arrows has changed. This apparently meaningless game of paradoxes leads us up to a very serious problem. For, in the words of G. Naan, confronted with two equally valid directions along the time axis, we judge of the direction toward the future solely by local physical processes, such as the increase of entropy (and our frantic struggle to prevent it from increasing).

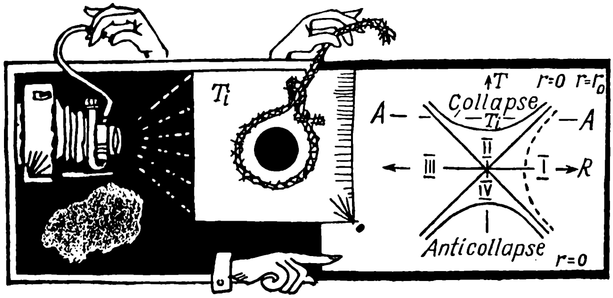
After a round-the-world trip in nonorientable space an observer would have to say that either time had flowed back-

ward or entropy has a tendency to decrease. Therefore the question which has been worrying researchers so much—how the energy of electrons in quasars can be boosted from several electronvolts without violating the second law of thermodynamics—may have a very simple, though from the point of view of habitual notions quite unexpected. answer: the gravitational field is so strong that it produces a spatio-temporal twist.

So much for our discourse on the nature of infinity or the topological properties of space. There are no isolated local problems in science. They are all interlinked in one way or another, displaying remarkable interdependence. Therein lies the great beauty of modern natural science. I have attempted to arrange the subject-matter of this book approximately according to the same principles. This explains the abundance of sudden deviations and frequent recurrence to questions already discussed. Science never ventures to put the final full stop. Most complete of its edifices can suddenly collapse, revealing contours of a more imposing structure.

Let us return to multiply-connected, nonorientable spatio-temporal sets. More specifically, our interest is in the problem of causality in "exotic" spatio-temporal domains. Possible anomalies in cause-and-effect links of phenomena can be excluded at once by a "one-way traffic" rule of sorts. The gravitational explosion or implosion of a superstar can normally present a fairly simple sight: matter can move only radially, inward to or outward from the centre. Reversal of motion and head-on motion are quite impossible. In the "catastrophe" region a motorist (assuming he could get there) would be incapable of suddenly changing his mind and turning back. His fate in such a domain is predetermined once and for all. Cause-and-effect links are much more rigid and definite than in ordinary space-time. In the catastrophe region even a round-the-world journey of the type we mentally made along the Möbius band is impossible. And all because every motion must either start in a catastrophe (explosive expansion from a point) or end in a catastrophe (implosive contraction to a point).

Let us try and analyse this on the Kruskal diagram. In this diagram the various hyperbolas correspond to different values of the Schwarzschild radius. Quadrant I represents the domain outside the Schwarzschild radius, quadrants II and III are domains within it.



Imagine ourselves as observers sufficiently removed from the Schwarzschild radius. As we approach it (the line $r=r_0$) the gravitational field increases and, as we know, the flow of time slows down. At the radius itself time flows infinitely slowly. Even with the utmost patience we can discover no apparent changes. Hence, to us, a falling object will never find itself within this radius (or will reach it in the infinitely remote future). In the same way, expansion or anticollapse (quadrant IV) begins in the infinitely remote past. Thus, for us the lines $r=r_0$ become the temporal limits of the world. One of them corresponds to an infinitely remote past ($t=-\infty$), the other, to an infinitely remote future ($t=+\infty$). But the whole of this endless river of time is not enough to embrace the collapse. For the whole thing is that motion within the Schwarzschild radius takes place before the beginning or after the end of eternity!

All this is for the case of a detached observer. Let us now see how a clock falling with a particle toward the Schwarzschild radius will behave. The whole fall, up to and including the motion within the radius (from the line $r=r_0$ to the hyperbola $r=0$), where the particle acquires the speed of light, takes place within a finite and not very long time interval.

Special relativity has reconciled us with the notion that every reference system has its own proper time. We cannot say definitely that the clock falling with the particle or the clock in the observer's hands is showing the "true" time. In both cases we must deal with objective reality. Only space-time is absolute: as soon as we split it into space and time we obtain relative concepts. The best course would, naturally, be to follow events in space-time. This, howe-

ver, involves a great deal of mathematics with complex world-line equations. Our common sense demands a separation of the concepts.

The collapse process involves overcoming the barrier set up by the Schwarzschild radius, which occurs as it were in a sudden leap, in a spatio-temporal explosion that simply defies description in conventional terms. Thus, in crossing the barrier one of the spatial coordinates changes places with the time coordinate. In conventional terms we would have to say that distance has become time and vice versa.

Nor do the strange features of the Schwarzschild radius end here. Thus, at the barrier itself space-time cannot, in principle, be separated. An observer reaching the limit would be in for some strange sensations indeed. All eternity, from the infinitely remote past to the infinitely remote future would contract into one imperceptible instant. Past, present and future would fuse into one. In other words, time would vanish. When he entered the domain corresponding to the hyperbola $r=0$, our observer would find that space, too, has disappeared, contracted to a mathematical point.

The age-old experience of mankind refuses to accept a situation such as this. Old logical concepts are too small for the notion, new ones have not yet been invented. New concepts inevitably come into conflict with common sense, with our sense of reality. How, for example, can we reconcile ourselves with the notion of multiply connected space? We are simply incapable of imagining space that is not a continuum. It is hard for us to imagine that in a multiply connected space not every contour can be drawn into a point within the contour by continuous deformation. And this is just the kind of multiply connected space our observer would encounter.

Take a plane perpendicular to the plane of the diagram and the T axis. It gives us a cross-section (the broken line A-A) of space-time at the instant T_i. In other words, it gives us an instantaneous snapshot of events in this exotic domain. For small time intervals ($T_i \to 0$) space possesses no outstanding features and the cross-section is an ordinary plane surface. Then, starting from some given time, the hyperboloid $r=0$ cuts a round hole in the plane. The picture offers a snapshot of the event.

Space has ceased being one simply connected. The outline around the hole cannot be drawn into a point. Its li-

miting boundary is presented by the edge of the hole. All trajectories (spatial projections of the world lines of particles) must stop at this insurmountable boundary. On the other hand, if we made a similar cross-section of the lower part of the diagram all trajectories would be compelled to start at the edge of the hole.

Any system leaving the conventional domains of space and entering the catastrophic domains (quadrant II in the diagram) will never return. More, it will not even pass into some other ordinary space-time. Its only path remains a catastrophic contraction to a point.

There is a logic in all this, however peculiar. As for the spatial domain corresponding to the hole (the black disk), it is quite unique in its apparent incomprehensibility. It is nothing. Complete and absolute nothing, which savants of past ages had sought in vain. It is a domain of non-space, non-time, non-matter, non-motion—of nothing. And yet we can't say that it doesn't exist. Because it does. Moreover, it can manifest itself. For at its boundary begins and ends the history of any object undergoing a gravitational explosion. In the case of collapse its history ends, in the case of anticollapse it begins. In other words, it is as though an anticollapsing superstar appears out of nothing, and a collapsing star vanishes into nothing.

These are all words we are forced to say, prompted by our whole system of reasoning, the principles of rationalizing and, most important, our semantic and associative vocabulary. It is extremely hard to say what we *really* have here. Apparently that which we are forced to call "nothing" is in fact some entirely new form of reality.

Naturally, it is hard to expect known forms of reality to change into unknown forms and back again according to known physical laws, as in that case the unknown form of reality would be knowable.

Since time immemorial men have tended to divide reality into a kind of "framework" (space and time) and "filling" (matter and field). It is only in the last few decades that we have, with some difficulty, come to realize that the "framework" represents a unity of space-time connected in some way with the unified "filling" of matter-field. The time has now come to get to the bottom of this mysterious connection and show that framework and filling are probably but two forms of a single reality. There is reason to ex-

pect that general relativity is gradually evolving from a description of the metric properties of space-time into a description of its topological properties. This means that the real departure from classical notions is yet to come. And perhaps Wheeler is right when he says that the "filling", far from determining the properties of the "framework", is itself no more than a corollary of certain unusual (topological) properties of it. Proceeding on the basis of this radical notion, we can regard quasars as a peculiar kind of warp in space-time, an anomaly in "conventional" topology.

The idea is an intriguing one, though perhaps not "mad enough" to explain the most spectacular of known processes in the universe. It is not, however, for this that we have launched this long and difficult discussion of infinities and spatio-temporal manyfolds. Our final conclusion, for which the reader should by now be at least partially prepared, is this: At present we arrange all forms of reality in an overall scheme of space-time and matter-field; but we may soon be compelled to alter it a little and write: space-time-matter-field.

All we have done here is to substitute a hyphen for the "and". But man and science have still a long and tortuous way to go before this hyphen is as fully recognized as the hyphen in Einstein's concept of space-time or the equality sign in the formula $E=mc^2$ linking matter (mass) with field (energy).

Only then will we be able to say that all existing things are but variations of the same reality.

SOME CLARIFICATIONS CONCERNING FINALITY AND INFINITY

And now we again return to the question of questions which excited men in Biblical times, in the ancient world, and the Middle Ages and continues to excite us today. We still have no way of knowing for sure what the space and time of the universe as a whole are like. We can only assume that the properties of space and time at vast distances are the same in the neighbourhood of the earth into which we launch satellites and manned spaceships. We have no way of verifying whether this is so, and who knows if we ever will. For that reason, in approaching the question of the finality or infinity of the universe it is best to forego

all hopes of a final answer. The ancients had it easier. The cosmology of ancient Babylon was a collection of myths which, of course, required no proof of their veracity. It was all so simple and clear: the god Marduk tore the monster Tiamat in two and created the heavens from the upper half of his body and earth from the lower.

But, joking aside, the problem of the finality or infinity of the universe cannot be approached without an understanding of the specific traits of cosmology that set it aside from all other sciences of nature. First of all, it must be realized that cosmologists are deprived of such a mighty means of cognition as comparison. It is in comparison that we establish the differences between, and similarities of, things. But the universe is unique and it encompasses the totality of all material existence. The universe is inimitable. It is always different, and we never know what processes taking place somewhere may be changing, or have already changed, it. The universe is inimitable, which makes it impossible to speak of laws applicable to it as a whole.

Take, for example, the law of universal gravitation. It is apparently valid for any two bodies in the universe, but what can the universe itself interact with if it is alone? Take the laws of thermodynamics. Energy is dissipated, entropy increases. This is a universal law valid for every isolated system. But can the universe be regarded as an isolated system if it has no surrounding medium? Nor is all this merely a case of sophisms or semantic paradoxes? It is first and foremost a question of the uniqueness of the universe. Everything else is deducible from this as corollaries. Hence, the task of cosmology is not the search for laws governing the universe as a whole but of building a model of it. Cosmologists even more than nuclear physicists must fight to overcome the inertia of thinking. The boundaries of so-called "common sense" are extremely relative. For the universe as a whole, at least, they are certainly too small. Specified direction in space, for instance, loses meaning when space expands to the dimensions of the universe. It is meaningless to speak of "left" or "right", "up", or "down". This is obvious. Less obvious, but no less meaningless, is it to speak of a one-and-only direction of development. If some entities evolve along an ascending line from simple to more complex, this by no means implies that such

is the law of evolution of the universe. Man, planet, even Galaxy is not yet the universe. Especially as all about us there are processes which follow a descending line, from higher to lower. An example is the evolution of superdense matter into diffused matter. Both directions are found in the universe, but none determines its life as a whole. The only thing that really characterizes the universe is the eternal recycling of matter. This idea of Engels, formulated in the introduction to his *Dialectics of Nature* to this day remains the most general and exact.

Democritus considered the universe to be infinite in space, and ancient dialectician Heraclitus thought it to be infinite in time. Christian cosmogony drew a picture of the world bounded by the crystal sphere of fixed stars and reckoned time from the creation to the end of the world. Copernicus merely shifted the centre of this world from the earth to the sun. It was Giordano Bruno who first loudly proclaimed the infinity and eternity of the universe. But we have spoken enough of history. The important thing for us is to show that the concepts of the finality and infinity of the universe have alternated through history. The succession of mutually contradictory ideas can be traced throughout the history of human thought. Negation of the negation is a cornerstone of dialectics. Without this law it is difficult to understand the inner contradictions of ideological struggle in science. The succession of opposing concepts is more than a simple replacement of one by the other. It is a complex, objective process which is quite independent of the will of individuals. However beautiful and streamlined the generalization of known facts by a scholar, something contradicting his system is always bound to appear. Nor can it be otherwise.

Newton's system clashed with the idea of the infinity of the universe. In 1774, Chezeau discovered the so-called photometric paradox. The idea is that a mean uniform distribution of stars in infinite space would, in infinite time, have heated the sky to the brightness of the sun. But as we all know it's dark at night. In other words, something was wrong: either the theory was in error or facts capable of explaining the photometric complex were undiscovered. But the paradoxes remained and even multiplied. Neumann in 1877 and Seeliger in 1899 discovered the gravitational paradox mentioned above, according to

which the uniform distribution of stars should create an infinite gravity pull at every point in space.

In an attempt to resolve the difficulties of theory, astronomers and physicists resorted to all kinds of *ad hoc* theories. Thus, the photometric paradox was explained by the existence of interstellar matter absorbing light. But in infinite time it, too, would have warmed up till it became a source of radiation. Scientists were forced to reject this unobservable world component which, more important, failed to resolve the problem in any case. Equally futile was an attempt to explain the Neumann-Seeliger paradox by the fact that gravity decreases faster than the inverse square of the distance.

The most gallant attempt to salvage the Newtonian system of the world was an hierarchic model of the universe worked out by Charlier and improved upon by V. G. Fesenkov in 1937. This model postulated an infinite universe with an infinite mass the density of which, however, tended to zero. This universe comprised systems of different steadily increasing orders of magnitude. The planets with their satellites were followed by the stars with their planets, star clusters, nebulae, clusters of galaxies, metagalaxies, clusters of metagalaxies, and so on, *ad infinitum*. As the model provided for a rapid decrease in density in going over to higher steps in the hierarchy the paradoxes were automatically resolved. This was the last tribute to self-evidence, a stupendous apologia of common sense.

However, long before that, when relativity theory had just appeared, it became apparent that the Newtonian system was no more than a special case of another, more general system. This has been said before. It would perhaps be appropriate to mention here an interesting episode in Einstein's life. Once the great man's nine-year-old son, Edward, asked him, "Papa, why are you so famous?" "You see," Einstein replied, "when a bug crawls over the surface of a sphere he doesn't notice that he has travelled along a curved path; I simply happened to notice it."

Since 1917 or thereabouts Einstein began work on a theory which could extend his equations to include cosmology. He encountered insurmountable mathematical difficulties which have not yet been resolved. That is why he introduced into his gravitation equations the celebrated cosmological constant which enabled him to create a mathe-

matical model of the universe. The mean density of matter in such a universe is constant and space, though unbounded, is closed in on itself. This is hard to visualize, but the two-dimensional model will help us once again. Meanwhile, however, we must first return to what was mentioned above only in passing. In 1922, G. A. Friedmann showed that a solution in which the mean density of the universe is not zero could be obtained without the cosmological constant. The only proviso was that the geometric properties of the universe must change with time. In other words, such a universe must either expand or contract.

Einstein's sphere with the little bug crawling over it could not expand and contract like a toy balloon. Einstein disagreed with Friedmann's conclusions and published a brief article to the effect. But later, after analysing Friedmann's arguments, he sent a letter to the editors of the German *Physical Journal*. This letter is an example of scientific integrity and human nobility. Here is this remarkable document:

"Comment on G. Friedmann's work, 'On the Curvature of Space'. A. Einstein, Berlin (Received 13 May 1923)

"In a previous article I criticized the above work. However, my objection rested on a mistake in calculation, which I discovered, on advice from Herr Krutkow, after reading Herr Friedmann's letter. I consider the findings of Herr Friedmann to be correct and exhaustive. The field equations, it turns out, allow, for the structure of space, along with static solutions, dynamic (that is, changing in time) central-symmetrical solutions."

Friedmann discovered two solutions of the gravity equation. From the first it derived that at some moment, which can be taken for the initial state of the universe, all distances were infinitely small and density was infinitely high. This was what the universe was like an instant before the "big bang". Though by using the words "an instant before the bang" we are guilty of an inaccuracy. For time itself "appeared" only when the clot of protouniverse began to expand. We are living in a universe that is still expanding. It may continue to expand infinitely. At least, this doesn't contradict the first solution of the equation. The solution gives us a model of the universe which is called "open".

The second solution also provides for an initial state, a superdense protouniverse whose stupendous gravitational

field cannot coexist with time. Then comes the explosion, the creation of familiar forms of matter and expansion. Everything is as in the first case, with one small exception: the expansion is not infinite. Some day the galaxies will cease fleeing in all directions, the stars will draw closer, pull in their planets and become centres of condensation of diffuse matter. The universe will contract back into a tight clot. This is the "closed" model of the universe.

The debate about the type of universe we are inhabiting, "open" or "closed", is still going on. So far our radio telescopes tell us that the remotest galaxies are receding at ever greater velocities. But who knows, perhaps somewhere further out, beyond the range of the most sophisticated antennas, galaxies are slowing down? So far we can only guess whether our universe has begun to contract or whether it is still expanding and will continue to do so eternally. Whatever the answer, man has at least 10,000 million years to wait—so the people really concerned with destinies of the world in which we are living are primarily mathematicians. This is a mathematical, not a human problem. For all practical purposes thousands of millions of years are as good as eternity.

That is one of the reasons why time and again people have been tempted to refute the incomprehensible mathematics which produces such "subversive" conclusions. One can argue with theory, but one can't refute facts. That is why the most heated arguments have developed around the interpretation of these facts. In the final analysis it can all be reduced to the red shift. The thought was expressed that visible extragalactic objects cannot be identified with the whole universe, which is immeasurably greater than the astronomical universe. But how do we know how much of the whole universe falls within the observable universe? And in general, what have we to say about the nonobservable universe besides a lot of fantastic hypotheses?

The idea has been expressed that extragalactic objects are not necessarily all receding from a "centre" and there may well be regions where they are converging on the "centre". But models of the universe simply have no centres! And galactic clusters are receding not from a nonexistent centre but from each other. And since no one has so far

discovered any clusters moving closer together there is again no basis for argument.

Finally, and this has been mentioned above, the idea has been expressed that the red shift may not necessarily be due to the expansion of the universe. Today, however, we can say quite confidently that modern science has dispelled the last doubts that the universe is expanding. It is a well-established observable fact. Therefore any attempt to evolve a theory of the evolution of the universe inevitably leads to the conclusion that our world was most likely once compressed into a very small and very dense volume. Hence the primary task of modern cosmology of re-creating by logical reasoning the processes which could have gone on in the superdense state and of proving unequivocally that the world about us is a result of these processes. Obviously, the apparatus of relativity theory alone is not sufficient. Without taking account of the laws of nuclear physics it is impossible even to start trying to imagine what superdense matter is like. Naturally, modern cosmology makes use of both Friedmann's theory of the expanding universe and nuclear physics. At the present level of our knowledge the question of the origin of the state of infinite density, as well as of the further evolution of the universe, can hardly be resolved. A quite feasible task, however, is that of re-creating the first stages in the expansion of matter. As mentioned briefly above, the first such hypothesis was enunciated by Gamow and subsequently developed by Alfven and Hermann. The computations for the hypothetical nuclear reactions were carried out by Fermi and Turkevich.

"However," writes Zeldovich, "in the light of contemporary knowledge the desire of these authors to obtain the observable abundance of chemical elements in every detail is naive. Today no one can deny that for thousands of millions of years complex nuclear synthesis reactions have been going on in the stars and the abundance of different elements must have changed as compared with what was formed immediately after the expansion began. In actual fact, there is only one crucial question: is the picture of expanding matter of infinite density compatible with our general ideas of the composition of prestellar matter and, especially, of the preponderance of hydrogen in it?"

THE SUPERDENSE "BOMB"

Initial theories about the composition of the primary prestellar matter treat it as having been made up almost wholly of neutrons. This seemed feasible because, as we remember, back in 1937 Lev Landau showed that on reaching a certain density matter turns into neutrons with a negligible admixture of electrons and protons. But the criterion of contemporary cosmogonic theories is the present distribution of atoms in the universe. Why do hydrogen atoms predominate among them? How did the earth's crust come to have so many chemical elements—practically the whole of the Mendeleyev table? These are questions that can be answered in a theoretical investigation of the superdense phase of the metagalaxy, when nuclear reactions proceeded with much greater intensity than today owing to the proximity of particles.

Strictly speaking, no theory of the evolution of the world is capable of resolving all questions. To explain a stage in the development of the world means to describe in strict scientific terms how this stage emerged from the preceding one. And what about the preceding one? How did it start? The question can be asked endlessly. But science would never have budged if it had engaged only in problems allowing for ultimate, all-embracing solutions.

A scientist who realizes that every scientific accomplishment is a step forward toward the truth is not discouraged by any amount of "whys?" and "wherefores?". Therefore any cosmogonic hypothesis is compelled to stop at some (more or less early) stage in the evolution of the metagalaxy, accepting that stage as a postulate, as something preordained. Obviously, the farther away from us in time this stage is the better for us. In the past much attention was given to the question of the origin of planetary systems.

At that time the stars were assumed to be eternal and requiring no explanation. As astronomy advanced works appeared which attempted to describe the spectacular processes of star formation from hydrogen filaments of negligible density. Finally, comparatively recently, the postulated phase of the universe was pushed back several thousand million years into a period of no stars or spiral systems, when the matter of the metagalaxy was compressed into a tight, virtually homogeneous ball.

Cosmogonic theories concerning the prestellar stage of the world were enunciated by theoreticians in the Soviet Union and the United States. Although in all cases the necessary computations were approximate, they provided a general explanation of many structural features of our world. These works presented the basic features of the evolution of the universe, drawing a majestic, impressive picture of the origin of the metagalaxy that extends before our eyes when we look up into the nocturnal sky.

It is interesting to note that the theories' respective values depend only fifty per cent on the type of model they employ: whether closed or open, there was a period in the past when matter was tightly packed. The differences between the two Friedmann worlds are projected into the future.

Physicists commence their exposition of the evolution of a closed-model universe from the time when the metagalaxy occupied a negligible volume of literally several cubic centimetres. Thus, an attempt is made to trace the evolution of the universe practically from the moment of its birth.

How long ago did the metagalaxy start its evolution from the superdense state? There is a way of gaining some idea of this by experiment. Astronomers have measured the so-called Hubble constant, which characterizes the present rate of expansion of the universe. It is equal to 75 kilometres per second for every million parsecs or three million light-years. This means that a galaxy three million light-years away (twice the distance of the Andromeda nebula) is receding from us at 75 km per sec. It is not hard to calculate that, neglecting, in the first approximation, any change in the rate of expansion, the galaxy was next door to us 40,000 million years ago. If the recession is assumed to have once been faster, the age of the metagalaxy must be reduced accordingly.

Cosmogonic theories employ mathematical means in an attempt to describe the initial stage of expansion and use it to explain the known properties of the world.

G. Gamow has suggested the following picture. In the initial stage, when the radius of curvature of the universe was only several centimetres, only neutrons existed. The temperature was relatively low and there was virtually no radiant energy.

The "neutron origin" hypothesis springs, evidently, from a desire to have only one fundamental, primordial particle. It had to be neutral as the universe as a whole has no electric charge. The fact that the contemporary universe is made up predominantly of hydrogen was not initially discouraging, since free neutrons have a lifetime of around one thousand seconds, after which they disintegrate into protons, electrons and antineutrinos. A proton and electron, of course, can always form a hydrogen atom—as soon as the universe expands sufficiently to give the particles enough "elbow room".

However, more detailed calculations soon revealed that before all the neutrons could disintegrate reactions between newly born protons and undecayed neutrons would start, jeopardizing the orderly picture. A sequence of nuclear transmutations encompassing all the matter in the universe in a matter of minutes would result in the formation of a large proportion of helium and other elements heavier than hydrogen. Being stable, after the expansion these elements would be incapable of transmuting back into hydrogen, creating a discrepancy with the observed compositions of stars and galaxies.

Thus, what at first glance seems to be an attractive theory of the origin of the universe from a superdense neutron fluid turns out to be insolvent.

The next step was made by Zeldovich. Reflecting on the contradictions between different cosmogonic theories he concluded that many of them could be removed by assuming the existence of three types of particles—protons, electrons and neutrinos—in the initial stage of the world.

This hypothesis assigns the neutrino a new and important role. As is known, a neutrino is produced, along with a neutron, in the fusion of a proton with an electron. According to Zeldovich, before these reactions began the primordial superdense mixture contained free neutrinos filling in the spaces between protons and electrons and preventing the interactions between them which would otherwise have started: at high densities of matter protons interact readily with electrons, yielding neutrons. The newly created neutrons, in turn, unite with the remaining protons to form nuclei of helium, lithium, beryllium, boron, etc. Within half an hour after the expansion began there would

be no protons or neutrons left in the clot, which would comprise heavier nuclei, from lithium up. This course of events is prevented by the neutrino background.

When the universe was very small and made up of equal quantities of primordial particles (electrons, protons and neutrinos), the number of neutrinos per unit volume was so great and their energies were so high that all the cells of the so-called phase space up to energies of 400 million electronvolts were occupied. The fusion reaction of a proton and electron into a neutron requires neutrino radiation in just this energy range. In accordance with Pauli's principle, this radiation was impossible, therefore no neutron breeding reaction was possible. The protons and electrons were preserved intact by the powerful neutrino background, which suppressed the fusion reaction.

A few words about phase space.

Particles with spin 1/2 (all particles except photons and mesons) obey the Pauli rule: in phase space there exist finite cells each of which can contain no more than one particle. If all the cells are occupied no new particle can appear as a result of decay. That is why there "was no room" for newly created neutrons.

Thus, the presence of energetic neutrinos "saved the lives" of the electrons and protons. What happened later when, because of the expanding world, the neutrinos began to dissipate energy and unoccupied cells began to appear in phase space? By then the electrons and protons had separated sufficiently widely appart for their fusion into neutrons to become highly unlikely in view of the low density of matter. It is thanks to the temporary screening effect of the neutrinos that the world has retained its high hydrogen content: as of today the universe is almost 90 per cent hydrogen.

Initially the density of the universe was equal to the density of nuclear matter, and a cubic centimetre of matter weighed a hundred million tons. Three minutes later the density had dropped to that of platinum, and fifteen minutes after that to the density of water. After ten hours the world was as tenuous as the air in your room. And today, thousands of millions of years after it all began, the average density of the universe is several protons per cubic centimetre.

The function of the neutrino component of the primor-

dial matter was exhausted when the danger of the fundamental particles fusing into neutrons passed. If not for the neutrino background the world would have been quite different from what we know it, with an entirely different proportions in the occurrence of elements.

ANTIWORLD: BORN THE SAME DAY, THE SAME HOUR

The hypothesis that our universe was hatched out of a superdense "bomb" like a chick out of an egg is indifferent to the great symmetry of the world. Yet antimatter imperatively demands full rights. It is quite possible to assume that matter and antimatter are twins born at the same place and at the same time. It is also natural to assume that both states of matter developed at some stage in the evolution of the superdense protomatter. The first cosmological theory which offered just treatment of antimatter was enunciated by the American physicist Goldhaber.

Goldhaber calls the initial embryo of the universe a **universon.** This initial superparticle decayed into a **cosmon** and **anticosmon.** As you have evidently already guessed, the cosmon originated matter, the anticosmon—antimatter. So far all this is sheer fantasy, at best a phenomenological "protohypothesis" which has yet to be elaborated. Goldhaber does not say why the universon suddenly decayed. All he does is draw a parallel with the decay of the theta-zero meson into a positive and a negative pion. Like these particles, the cosmon and anticosmon flew off in different directions, speeding away from the place of decay as fast as possible. The explosion of the cosmon that subsequently occurred gave rise to the world we know. As for the anticosmon, it may not have exploded to this day. Or it may have at the same time as the cosmon, in which case the antiuniverse lies beyond the limits of visibility.

Goldhaber's hypothesis is as it were a stage preceding the hypothesis of the universe's origin from protomatter. It introduces the symmetry element lacking in other hypotheses, but otherwise it contains all their inherent drawbacks. We do not know where the universon came from nor why it suddenly disintegrated into two opposite particles. This is no better than the postulate of superdense protomatter compressed to a handful. There is nothing we can do about it. As physicists say, the origin of the universe

belongs to the category of "unpleasant" problems. As Professor I. M. Khalatnikov aptly remarked:

"People for the first time hearing of the remarkable achievements of cosmology quite naturally ask, what was there before the universe appeared? But, if there was a beginning of time, the question is not legitimate, since the concepts 'before' and 'after' are quite meaningless in the absense of the concept 'time'."

This is something we must reckon with. If we accept that the universe started with a "bang" then we must accept that time too began at that moment. "Before" that the clock stood still—or rather, it wasn't there at all. Therefore let us agree that all questions about what was "before" simply have no meaning. This will help us to take a new view of many "unpleasant" problems, which differ from the hypotheses of early natural philosophers only in that they rest on the whole might of experimental and theoretical sciences, whereas the natural philosophers relied on their imaginations for inspiration.

So let us not ask what there was before the beginning of the world. St. Augustine, they say, queried what God was doing before he created the world. To this question there are two equally unpleasant answers: (1) he didn't exist before he created the world; (2) he was busy creating Hell for people asking foolish questions.

Unlike Goldhaber, whose theory, whatever its faults, is based on the observed expansion of the universe, Swedish astrophysicists Alfven and Klein attempt to derive the metagalaxy from a cloud of extremely rarefied matter. There is not much to be said for such an approach, although their theory contains several clever ideas which give food for thought. Besides, the dialectics of the development of scientific thought suggests that the most correct solution is usually born at the junction of two diametrically opposing views. We shall overlook, to say the least, the rather vague initial premise in Alfven and Klein's theory, according to which the initial cloud appeared as a result of a small fluctuation in the energy state of space. Our knowledge of the nature of physical vacuum does, after all, enable us to digest such ideas. Thus, we start out with an energy fluctuation (and who is to say that it is worse than a "big bang"?). Pure energy can turn into an equivalent number of particle-antiparticle pairs. In effect, the Alfven-

Klein cloud is a plasma. In the first instants of its existence it is so rarefied that collisions between particles are very rare and particle-antiparticle annihilation is all but impossible. Then, gradually, gravitational forces cause the plasma to contract. Bursts of annihilation occur more and more frequently and their end products—photons—pervade space in ever increasing streams. The radiation pressure increases until finally the contracting and expanding forces are balanced. In these conditions the formation of atoms takes place, they gather into clouds of gas which gradually condense into various celestial bodies.

So far the Swedes' theory is fairly trivial. The most interesting point of it, though, is the idea of the separation of matter and antimatter. It is worth examining closer as it can to some degree supplement other, more viable cosmological theories. Which is not to say that it doesn't possess value of its own.

When the primary plasma was contracting—probably a highly erratic process—various local condensations developed. Owing to higher annihilation density, the temperature in these condensations must, evidently, have been higher than in the surrounding gas. This in turn produced convection. Under the action of gravitational forces the lighter electron-positron gas began to accumulate in one region, which we can arbitrarily call the "upper" one. The heavier gas, enriched with nucleons and antinucleons, gathered in the "lower" region. The motions of charged particles in the plasma generated electromagnetic forces which "sorted out" particles with opposite electric charges. There is no need to go into the details of the mechanism of electromagnetic separation of particles in the "upper" and "lower" regions: we are more concerned with the end result. And we know it in advance, since in our world particles vastly outnumber antiparticles. Our ultimate need is to join positrons and antiprotons, electrons and protons, and separate matter from antimatter. Alfven offers a hypothetical scheme of magnetic fields in the contracting cloud in which the electric currents needed for the separation process are induced. The scheme is arbitrary, of course, but it is also feasible, and what more can be required of an initial hypothesis dealing with one of the most unpleasant of problems?

After accepting, with due assumptions and reservations,

that the evolution of the primordial plasma eventually resulted in the formation of clouds of hydrogen and antihydrogen, we are immediately confronted with a new difficulty: how were these clouds kept from mutual annihilation?

Just as magnetic lines of force can be coiled into a tube in which plasma can be kept like water in a bottle, in future a "bottle" for keeping antiparticles may be created. Not a single charged particle will be able to pass through its invisible magnetic walls from within or without. Stocks of antiparticles can be safely kept in such a vessel without fear of annihilation. In other words, man will learn to screen matter from antimatter. But we are speaking of hypothetical processes which took place thousands of millions of years before the appearance of man. Alfven describes a method of spontaneous reciprocal screening of clouds of hydrogen and antihydrogen. Annihilation inevitably takes place at the boundary of these clouds. But that is quite all right. The annihilating atoms and antiatoms produce vortices of photons and electron-positron pairs. Like steam which supports a drop of water on a red-hot stove, this radiation gas hurls the clouds of antipodes in opposite directions. The more intense the annihilation process the more energetic the separating forces, and the clouds are blown apart almost as soon as they come into contact. For simplicity's sake we have been speaking of only one pair of opposite clouds, but a great number of them will have appeared in the primordial plasma. Then the most interesting thing begins. The magnetic fields in the primordial plasma are extremely weak: one or two gauss at the very most. But the weaker the magnetic field the weaker the current in the natural plasma circuit. This, in turn, means that fewer particles take place in the cosmic separation processes. Alfven and Klein estimate that magnetic fields of average strength are capable of separating matter and antimatter the total mass of which is commensurate with the mass of a star. This is a very important conclusion, for it means that our very ordinary stellar system could have originated not from one hydrogen cloud, but in the accretion of several such clouds. The obvious conclusion is that half the stars of the Milky Way must be made of antimatter!

Astronomers will have to work hard to challenge this startling conclusion. Light from stars carries no informa-

tion about the matter that emits it. Thus, our closest neighbours, such as Alpha Centauri or Tau Ceti, may well be deriving their energy from the synthesis of antiprotons.

However, although electromagnetic radiation is the same for matter and antimatter, there are subtle ways of discovering antiworlds around us—provided, of course, that they exist at all. Leaving aside neutrino astronomy, a science of the future, we shall consider so-called fronts: an analogy with atmospheric fronts which develop when cold and warm air currents meet. An atmospheric front is readily observable by frequently spectacular weather displays. Similarly, it should be possible to discover an annihilation front in outer space. As annihilation currents swirl at the boundary between matter and antimatter, the respective sections of the night sky cannot fail to reveal themselves in what astronomers call "gamma light". True, the earth's atmosphere blocks X-radiation from space, but satellites have already been used for orbiting gamma telescopes. The first experiments, to be sure, showed the cosmic gamma background to be fairly uniform. However, hundreds of precision measurements are needed before any final conclusions can be drawn. Besides, gamma telescopes are still too crude for us to use them as grounds for rejecting the idea of "nearby" antiworlds.

Another possibility of confirming or refuting the Swedish astrophysicists' theory has been suggested by the Soviet scientist N. A. Vlasov, who pointed out a peculiar feature of annihilation fronts. As we know, for a brief instant before annihilation particles and antiparticles form quasi-atomic structures: protonium (a proton-antiproton pair) and positronium (an electron-positron pair). Protonium and positronium possess excess energy. Therefore, before vanishing, they emit light quanta. Quasi-atomic structures must, obviously, possess specific spectra. What Vlasov suggests is to study the spectra of even the very weakest glows in space in the hope of stumbling on radiation of a spectral composition characteristic of quasi-atoms in annihilation fronts.

THE INEXHAUSTIBLE UNIVERSE

Having discussed at length what *was*, let us now turn to the equally burning problem of what *will be*. G. A. Friedmann produced his models in 1922-1924. Almost half a

century has passed since then. Let us see what new ideas modern science has injected into the exciting problem of the destinies of the universe. It must be said at once that so far no changes of principle have occurred in this field. This is only natural. The general theory of relativity remains to this day the best of all the known systems of the world. Einstein's gravitational equations are still the focus of painstaking, diligent scrutiny by theoreticians. Several years ago well-known Soviet scientists E. M. Lifshits and I. M. Khalatnikov undertook to reassess Friedmann's calculations. They came to an extremely interesting conclusion. It turns out that the closed model of the universe is a result of an idealization of the universe, a result of the purely mathematical simplifications the Friedmann had to employ in his calculations.

Complicated calculations carried out by Lifshits and Khalatnikov were crowned with the optimistic conclusion that the universe will never return to the superdense state, and even if it does start contracting again the process will be a limited one. The stars, at least, will not fuse together. True, these conclusions are not yet final, and Friedmann's models remain on the order of the day.

The most important thing is that, in the person of man, nature has been able to probe its fate. This may be only a first step, a vague estimate, but what a tribute to the might of man! How bold and daring the very thought of undertaking to foretell the fate of the universe!

In 1955, the Soviet astronomer A. L. Zelmanov showed that when the observed nonhomogeneities of the universe are taken into account in solving the gravitational equations, even in the first approximation, assuming zero average density of matter, the number of frames of reference in which the universe is infinite is also infinite. And by the same token, the number of frames of reference in which the universe is spatially finite is also infinite. Subsequent development of these works led Zelmanov to the conclusion, in 1963, that even in a "finite" universe the conventional concepts of "finite" and "infinite" are hardly applicable. It is obvious that there is no way of directly proving the finality or infinity of the universe. After all, human experience is finite. Very great, but finite, are the possibilities of the human brain, finite is the number of people who will ever have lived on earth. It would probably be wrong

to assume that there exists an absolute philosophical concept of infinity which would be independent of the concrete results produced by natural science.

Even more involved than the question of the finality or infinity of space is that of the finality of time. Space is more readily visualized than time. It is hard to grasp the notion of time in any concrete way. Time is inseparably associated with space, but this does not make the task much easier. Therefore, so as not to waste time, let us outline the possible "models of time". Apparently there are two: the time of the universe is either finite or infinite. Hence we can picture four possible models of the universe as regards space-time:

(1) infinite in space and time;
(2) finite in space, infinite in time;
(3) infinite in space, finite in time;
(4) finite in space and time.

It should not be imagined, however, that when we speak of the finality of time we necessarily have in mind its beginning and end. There is a subtle difference between the concepts of "finite" and "bounded". That which is bounded is certainly finite, but that which is finite need not necessarily have boundaries, a beginning and end in the present case.

Consider once again our intelligent flatlanders. Only now let them inhabit a vanishingly thin ring. This brings them into a world of one dimension, length. Obviously, the creatures have not the slightest notion of width and height. Such a one-dimensional Columbus undertaking to circumnavigate his world would make a great discovery. In the first place, he encountered no obstacles, meaning that his world has no beginning or end. In the second place he has managed to measure the length of his world, which, evidently, would mean that it is finite. So now imagine how the poor creature is to extricate himself from this mess of two mutually exclusive truths.

The problem of closed time is of the same kind, and we are all in the same position as the one-dimensional explorer. The conventional concept of time is simply inapplicable to the universe as a whole. So clear and concrete within the limited confines of our experience, it loses meaning.

The problems of finality and infinity are equally acute in cosmogony as in domains of physics or cybernetics which

have nothing to do with the destinies of the universe. Mathematicians have even suggested doing away with infinity altogether so as to remove a number of contradictions. The electronic mathematics of computers is also uncomfortable with the concept of infinity. It is too aloof, too ideal and philosophical! All the more so as no one has yet been able to prove that the concept is not just an abstraction lacking any analogues in the surrounding world. This is new and startling. But it may just be true. It may be worth pondering whether we haven't grown too used to the concept of infinity. Lobachevski declared that there is no such thing as parallel lines, and our world has been none the worse for it. On the contrary, it has become richer and more sophisticated. Perhaps the same can be said of infinity? All we have to do is reject it and the Gordean knots will untangle themselves.

The concept of infinity has played a tremendous part in the history of our civilization. Without it differential and integral calculus would perhaps never have been created. Yet this should not prevent us from undertaking a reassessment. Especially as it will not be all that radical. It is only a matter of principle. It is not at all simple to declare infinity finite. But what if infinity is no more than a synonym for a "very big" or "very small" uncertainty? Can we reason along such lines? Undoubtedly. More important, it involves no undermining of foundations. Everything remains in place. All we do is get rid of an almost mystical abstraction we have long ago grown used to. Now our dilemma concerning the infinity or finality of the universe has become doubly absurd.

Perhaps on this note we can conclude our story of the destinies of the world. But there is one more illusion that must be done away with. They say that as man is mortal he derives consolation from the infinity of the universe. The thought may not be so indubitable. But whatever the case, it is not the purpose of science to flatter either human weaknesses or human might. By encroaching on the infinity of the universe science robs people of nothing. The universe remains inexhaustible and unimaginably vast in time and space when compared with our human scale.

The task of intelligence is to cognize the world. And the world is inexhaustible.

And so stands Man, proud and mighty, at an intersection of great roads. With every passing day the horizon recedes farther and farther, but the roads are without end.

My feet firmly planted on the globe,
I hold aloft the sphere of the sun.
I am a bridge between earth and sun.

With these words of Eduardas Miezelaitis the author bids the reader farewell and thanks him for sharing the hardships of the long and difficult road from minute particles to the whole universe, from hazy prehistoric millennia to the present day.

TO THE READER

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